UNIVERSIDADE ESTADUAL DE CAMPINAS
Faculdade de Tecnologia

LAIS PEIXOTO ROSADO

LIFE CYCLE ASSESSMENT OF CONSTRUCTION AND DEMOLITION WASTE MANAGEMENT IN A BRAZILIAN WATERSHED

AVALIAÇÃO DO CICLO DE VIDA DO GERENCIAMENTO DOS RESÍDUOS DA CONSTRUÇÃO CIVIL EM UMA BACIA HIDROGRÁFICA NO BRASIL

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Thesis presented to the School of Technology of the University of Campinas in partial fulfillment of the requirements for the degree of Doctor in Technology, in the area of Environment.

Tese apresentada à Faculdade de Tecnologia da Universidade Estadual de Campinas como parte dos requisitos exigidos para a obtenção do título de Doutora em Tecnologia, na área de Ambiente.

Supervisor: Dra. Carmenlucia Santos Giordano Penteado

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RESUMO

No âmbito do gerenciamento dos resíduos sólidos, os resíduos da construção civil (RCC) representam um dos maiores desafios para o poder público, devido ao grande volume e altas taxas de geração, principalmente em municípios de médio e grande portes. Os RCC possuem alto potencial de reutilização e reciclagem, no entanto, tais práticas são incipientes no Brasil, sendo a disposição final em aterros a principal alternativa de gerenciamento adotada pelos municípios. Nesse contexto, o objetivo deste estudo consistiu em avaliar o desempenho ambiental do gerenciamento dos RCC nos municípios representativos das Bacias Hidrográficas dos Rios Piracicaba, Capivari e Jundiaí, localizados no Estado de São Paulo, por meio da Avaliação do Ciclo de Vida, a partir da abordagem atribucional. Todas as etapas do sistema de gerenciamento dos RCC conduzidas pelo poder público municipal foram consideradas e, os impactos ambientais potenciais foram avaliados por meio das metodologias CML *baseline* (v3.03) e Impact 2002+ (v2.12). Os resultados obtidos por ambas metodologias evidenciaram a importância dos impactos evitados provenientes dos materiais recuperados, principalmente àqueles advindos da reciclagem do metal ferroso, do vidro e dos plásticos. Em específico, a metodologia CML *baseline* indicou a categoria de impacto "Toxicidade Humana" como a mais importante, principalmente devido aos impactos evitados da reciclagem do metal ferroso e dos impactos gerados de todas as etapas de transporte do sistema de gerenciamento dos RCC. Por outro lado, a metodologia Impact 2002+ indicou as categorias de impacto "Efeitos Respiratórios Inorgânicos" e "Aquecimento Global" como as mais importantes, devido aos impactos evitados da reciclagem do metal ferroso e dos impactos gerados da etapa de transporte dos resíduos sólidos para o aterro. Na fase de interpretação, a análise de sensibilidade consistiu na avaliação de cenários alternativos para o gerenciamento da fração mineral e, na análise do efeito da variação de alguns parâmetros, como o transporte, composição do RCC e modelagem das emissões da disposição dos resíduos em aterro. Os resultados demonstraram as vantagens ambientais do aumento das taxas de reciclagem em conjunto com a melhoraria da qualidade dos agregados reciclados e, revelaram que determinadas variações na composição dos RCC podem afetar significantemente os resultados; desse modo, o controle do fluxo de resíduos é fundamental para a determinação do desempenho ambiental do sistema de gerenciamento dos RCC.

PALAVRAS-CHAVE: resíduos da construção civil; avaliação do ciclo de vida; fração mineral; reciclagem; gerenciamento.

ABSTRACT

In the context of solid waste management, the construction and demolition waste (C&DW) represents one of the greatest challenges for the public authorities, mainly due to the large volume and high generation rates, especially in medium and large-sized municipalities. C&DW has high potential for reuse and recycling, however, such practices are incipient in Brazil; therefore, the final disposal in landfill consists the main management alternative adopted by the municipalities. In this context, this study evaluated the environmental performance of the C&DW management in the area of Piracicaba, Capivari and Jundiaí Watershed, located in the São Paulo State, Brazil, by means of an attributional Life Cycle Assessment. The entire C&DW management under the responsibility of the municipal government was considered. The potential environmental impacts were assessed by using two specific life cycle impact assessment methodologies, CML baseline (v3.03) and Impact 2002+ (v2.12). The results obtained by both methodologies highlighted the importance of the avoided impacts from recovered materials, mainly those related to steel, glass and plastics recycling. In particular, the CML baseline indicated "Human Toxicity" as the most important category, mainly due to the avoided impacts from steel recycling and the generated impacts from transportation in all the C&DW management stages. The Impact 2002+ highlighted instead the role of the categories of "Respiratory Inorganics" and "Global Warming", in accordance with the results related again to steel recycling and transportation but also to landfilling of solid residues. In the interpretation, the sensitivity analysis consisted of the evaluation of alternative scenarios for the mineral fraction management and, in the analysis of the effect of the variation of some parameters, such as the transportation, C&DW composition and landfill modelling. The results highlighted the environmental advantages of increasing recycling rates along with improving the quality of recycled aggregates and, revealed that variations in the C&DW composition may significantly affect the results, which suggests that the control of the waste stream is fundamental to determine the environmental profile of the C&DW management system.

KEYWORDS: construction and demolition waste; life cycle assessment; mineral fraction; recycling; management.

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ACRONYMS

ABNT – Brazilian Association of Technical Standards

ABRECON – Brazilian Association for the Construction and Demolition Waste Recycling

ABRELPE – Brazilian Association of Public Cleaning and Special Waste Companies

BAMB – Building as Material Banks

BDTD – Brazilian Digital Library of Theses and Dissertations

BIM – Building Information Model

C&DW – Construction and Demolition Waste

CETESB –Environmental Agency of São Paulo State

CONAMA – Brazilian Council of Environment

GDP – Gross Domestic Product

IBGE – Brazilian Institute of Geography and Statistics

IPT – Institute of Technological Research

LCA – Life Cycle Assessment

NA – Natural aggregate

NBR – Brazilian Standard

PCJ – Piracicaba, Capivari and Jundiai

PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analyses

RA – Recycled aggregate

SIGOR – System for Online Solid Waste Management

SNIS – National Information System on Sanitation

WTC – Waste Transport Control

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CHAPTER

1

INTRODUCTION

The construction industry is an important sector of the global economy, mainly because of its infrastructure works and the potential of job creation, which have great influence in the development of a country. On the other hand, this sector needs special attention regarding its environmental aspects, mainly those related to the natural resources consumption and solid waste generation.

In 2014, 45 billion tonnes of natural aggregates were consumed, accounting for about 70% of the world's total mineral production. In the same year, 741 million tonnes were consumed in Brazil (ANEPAC, 2015). Despite the abundance of natural aggregates reserves in Brazil, there are economic and environmental constraints that influence the relation between the quantity of existing reserves and those that are reasonably available for use. For instance, the low price of the natural aggregates demands reducing the distance between the extraction site and the consumer market; it is estimated that extraction sites should be located at a maximum distance of 100 km from the consumer market to ensure the economic viability. From the environmental point of view, the natural aggregates production generates noise and air pollution, landscape degradation, depletion of natural resorces, among others environmental impacts (LA SERNA; REZENDE, 2009).

In addition to the high resource consumption, the activities of construction, renovation and demolition generate large amounts of wastes, which comprise a serious environmental problem in many countries. In 2017, the Brazilian municipalities collected about 45 million tonnes of construction and demolition waste (C&DW), which means a generation rate of 0.6 kg/inhabitants/day. In fact, the generation is even higher, since this amount refers only to the C&DW managed by the municipalities, not including wastes from large generators, such as building contractors (ABRELPE, 2018).

The C&DW is composed mostly by mineral fraction (ceramic components, mortar, concrete, soil, and others), which has a high potential for reuse and recycling as aggregates, when properly segregated (CARNEIRO *et al.*, 2001; JOHN, 2001; MARQUES NETO, 2003; BLENGINI; GARNARINO, 2010; SINDUSCON-SP, 2015). The Brazilian standards provide the requirements for the use of recycled aggregates in the production of non-structural concrete and as material for base, subbase and subgrade reinforcement of roads (ABNT, 2004a; 2004b). Currently, it is estimated that less than 20% of the C&DW generated in Brazil are recycled for utilisation in rural road maintenance and, as base and subbase material in road construction (ABRECON, 2015); the remaining C&DW are sent to inert landfills, reused as backfill material or disposed in illegal areas.

The main reasons of the low recycling rates are the absence of public policies that encourage the recycled aggregates consumption along with the lack of technical knowledge of the consumer market on the use of recycled aggregates (MIRANDA, 2005; ABRECON, 2015). Moreover, the high content of impurities in C&DW, resulting from mixing the mineral with the non-mineral fraction (metals, plastics, paper and paperboard, glass, hazardous materials, etc.), impairs the quality of recycled aggregates, reducing their price and market acceptance (ABRECON, 2015; BORGUI; PANTINI; RIGAMONTI, 2018).

The CONAMA Resolution nº 307/02 divides the C&DW generators into small and large, and the municipalities define the criteria for their classification. Usually, small generators are defined as those that generate less than 1 tonne of C&DW per day and, large generators those that generate more than 1 tonne of C&DW per day. In this sense, this Resolution determines that both generators are responsible for the C&DW management, but, the municipalities must provide infrastructures for receiving, sorting and temporary storage of small volumes of C&DW and, at the same time, encourage and supervise the proper management of the C&DW from large generators (BRASIL, 2002). It is important to note that about 70% of the C&DW generated are from small constructions, renovations and demolition works; and the remaining are from formal construction and demolition sector (SÃO PAULO; SINDUSCON, 2012).

Despite the existence of legal requirements on C&DW (BRASIL, 2002; 2004; 2010; 2011a; 2012a; 2015), due to the scarcity of technical and financial resources, as well as lack of supervision by the environmental agencies (SCREMIN; CASTILHOS JUNIOR; ROCHA, 2014), most Brazilian municipalities often adopt corrective measures in the C&DW management, resulting in high costs for public cleaning systems and environmental impacts related to the illegal waste disposal (MARQUES NETO, 2009).

In order to improve this scenario, the municipalities must develop and implement a C&DW Management Plan in accordance with the requirements of CONAMA Resolutions (BRASIL, 2002; 2012a) and National Solid Waste Policy (BRASIL, 2010), taking into account a reliable diagnosis of the local characteristics and peculiarities. After the publication of CONAMA Resolution nº 307/2002, several studies have been conducted to assist the municipal C&DW management (TAVARES, 2007; VEIGA, 2008; MARQUES NETO, 2009; BRÖNSTRUP, 2010; CÓRDOBA, 2010; SILVA, 2010; CALDAS, 2016; LOCH, 2017; VARGAS, 2018), providing a set of data on C&DW generation and composition of a specific region as well as suggesting management strategies to the policy makers.

In this context, it is important to analyse the environmental impacts resulting from the proposed strategies for solid waste management. This analysis requires systematic methods of collecting and comparing data, which must be interpreted in an appropriate way to be useful in the decision making process. Life Cycle Assessment (LCA) is one of the most appropriated methodology to obtain a reliable quantification of environmental impacts of a product or service, and has been used to evaluate solid waste management systems (CLIFT; DOIG; FINNVEDEN, 2000; MCDOUGALL *et al.*, 2001; SANER; WALSER; VADENBO, 2012; LAURENT *et al*., 2014; BOVEA; POWELL, 2016).

The LCA methodology allows to determine the environmental profile of the current C&DW management system and the comparison with other alternatives, providing results that may be used to justify investments in new technologies, to indicate the waste flow that must be sorted and sent to reuse or recycling, as well as, to quantify the environmental benefits (avoided impacts) obtained from these practices (CLIFT; DOIG; FINNVEDEN, 2000; COLTRO, 2007; CLEARY, 2009; LAURENT *et al*., 2014a).

The LCA studies applied to C&DW management are increasing, especially from 2010 to date, and they have been developed to verify the environmental impacts of end-of-life of buildings (COELHO; BRITO, 2012; ZAMBRANA-VASQUEZ *et al*., 2016; VITALE *et al*., 2017), compare the benefits of recycled aggregates versus natural aggregates (MARINKOVIC´ *et al*., 2010; FALESCHINI *et al*., 2016; ROSADO *et al*., 2017), determine the environmental impacts of recycling processes (MERCANTE *et al*., 2012; COELHO; BRITO, 2013; LOCKREY *et al*., 2018), and analyse the environmental profile of C&DW management systems (ORTIZ; PASQUALINO; CASTELLS, 2010; BUTERA; CHRISTENSEN; ASTRUP, 2015; PENTEADO; ROSADO, 2016; HOUSSAIN; WU; POON, 2017; DI MARIA; EYCKMANS; ACKER, 2018; BORGHI; PANTINI; RIGAMONTI, 2018; YAZDANBAKHSH, 2018).

In accordance with a literature review of 222 LCA studies applied to evaluate the environmental performance of solid waste management systems (LAURENT *et al*., 2014a), only two studies have been developed in Brazil, both elaborated by Mendes, Armaki and Hanaki (2003; 2004) and, only three are specific on C&DW management. In addition, a literature review of 80 LCA studies applied to C&DW management published until 2014 (BOVEA; POWELL, 2016), only one study refers to the Brazilian context, developed by Condeixa, Haddad and Boer (2014). Although the increase of Brazilian theses and dissertations related to LCA, only few studies are focused on solid waste management (PASQUALI, 2005; FERREIRA, 2009; DMITRIJEVAS, 2010; PETROLL, 2010; PAES, 2013; BARRETO, 2014; ROSADO, 2015; ZAPPE, 2016), of which, only four refers to C&DW management (PASQUALI, 2005; FERREIRA; 2009; BARRETO, 2014; ROSADO, 2015).

Considering the existence of few LCA studies applied to C&DW management at municipal level, both in the international and Brazilian context, there is no consolidated methodological approach related to this type of study. Thus, the main motivation of this study was to develop a LCA model to evaluate the environmental profile of the C&DW management system in a municipality or in a set of municipalities. For this, the following hypothesis was verified: *"the LCA methodology allows the analysis of the current environmental profile of the municipal C&DW management system and its comparison with alternative scenarios, in order to provide guidelines for the decision making process on the municipal management level"*.

In order to verify the hypothesis, the municipalities of Piracicaba, Capivari and Jundiaí Watershed (PCJ Watershed), located in the São Paulo State, were defined as the object of study. Particularly, a watershed was selected since it can be considered an appropriate spatial scale to assess the impacts of current urban occupation (MINISTÉRIO DAS CIDADES, 2004). The PCJ Watershed is an organizational model for the other watershed committes, and represents 0.18% of the Brazilian territory, 2.7% of the population and 6% of the GDP (Gross Domestic Product) (COBRAPE, 2011).

1.1 AIM OF THE STUDY

The overall objective of this study is to evaluate the environmental performance of the construction and demolition waste (C&DW) management in the municipalities of Piracicaba, Capivari and Jundiai (PCJ) Watershed, located in the State of Sao Paulo, Brazil. The Life Cycle Assessment (LCA) methodology was used to evaluate the environmental performance of the current C&DW management and alternative scenarios. The specific goals are:

- To gather data about the current C&DW management system in the PCJ Watershed;
- To select the representative municipalities according to the C&DW generation;
- To identify and quantify the environmental burdens of the C&DW management of the selected municipalities in order to elaborate the Life Cycle Inventory;
- To evaluate the potential environmental impacts of the current C&DW management systems of the selected municipalities and alternative scenarios;
- To recommend potential measures to improve the management system of the C&DW from small generators.

1.2 THESIS STRUCTURE

This thesis is structured in six chapters. This **first chapter** presents an overview about the research topic, justification and main objectives of the study.

Chapter 2 presents the literature review about C&DW, including its characteristics and the current management system adopted by the Brazilian municipalities. In addition, this chapter presents a set of studies focused on C&DW management in the international and Brazilian context. Finally, it presents a content about watershed as planning unit for solid waste management.

Chapter 3 comprises a literature review about Life Cycle Assessment (LCA), including the origin of this methodology and its four main stages (goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation). This chapter also presents the main studies about LCA applied on C&DW management.

Chapter 4 refers to the methodology used in this study, which is composed by three main steps: (i) selection of the representative municipalities from Piracicaba, Capivari and Jundiaí Watershed; (ii) collection of primary data, and (iii) the methodological stages of the life cycle assessment study, namely “Goal and scope definition” and “Life cycle Inventory”.

Chapter 5 presents the “Life Cycle Impact Asssessment” and “Interpretation” stages. In addition, it comprises the discussion of the results and some recommendations of potential improvements on the management system of the C&DW from small generators. Finally, **Chapter 6** presents the conclusions and suggestions for future research.

The **Appendixes** include the supplementary materials that support the data presented throughout the study.

It is worth to note that the main results, discussion and conclusions of this thesis have been published in Rosado *et al*. (2019). The **articles** and **conference proceedings** related to this doctoral thesis, published or submitted, are listed in the final part.

CHAPTER

2

CONSTRUCTION AND DEMOLITION WASTE

The construction industry is one of the most important sectors of the global economy, being considered crucial to the economic growth of a nation. This sector accounts for about 5% of total GDP (Gross Domestic Product) in developed countries, while in developing countries it accounts for more than 8% of GDP. It is expected a great growth of the construction industry in the upcoming years (WE FORUM, 2016), with estimated revenues of $15 trillion by 2025, and three countries (China, United States and India) accounting for 57% of the global growth (GCP GLOBAL, 2015).

In Brazil, it was estimated that the investments in construction achieved approximately R$ 592 billion in 2016[1], which is equivalent to 9.3% of the GDP in the same year. In that period, the construction activities employed 12.5 million people, representing 13.7% of the total number of employees in the country (CONSTRUBUSINESS, 2016).

In recent years, institutional changes have contributed for increasing public and private investments in urban development in Brazil, such as reinstatement of the housing financing system (Law 10.931/2004); regulatory framework for sanitation (Law 11.445/2007) and National Policy on Urban Mobility (Law 12.587/2012). The Federal Government Program “My Home My Life” is one example of Brazilian initiatives, which aimed to deal with the international economic crisis and reduce the housing deficit. However, the years of 2015 and 2016 were recognized by the scarcity of public investments in housing financing (CONSTRUBUSINESS, 2016).

In this context, Brazil still requires meaningful investments in urbanization (housing, sanitation and mobility) and infrastructure (energy, transport and telecommunications). Therefore, according to data from Construbusiness (2016), the main demands of investments in infrastructure in Brazil are: (i) building of 8.810 million houses, between 2017 and 2022, in order to assist the new families, eliminate substandard housing and the housing deficit; (ii) installing 8.184 million new water connections and 9.951 million new

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[1] 1 R$ = US$ 0,26 (exchange rate obtained in 12th April, 2019).

sewage connections, between 2016 and 2022, to provide water distribution for 95% of the houses and sewage collection for 80% of the houses; (iii) investing R$ 684.5 billion in infrastructure, of which about 60% for the transport sector, 15% for the electric energy sector, 18% for the mineral production and 7% for the telecommunications .

These investments present a clear benefit for the life quality of people, however, construction activities have economic, environmental and social impacts, which must be minimized during the planning phase. Thus, the use of new technological tools should be encouraged, such as Building Information Model (BIM) and 3D printers, which can increase productivity, reduce project delays, improve construction quality and working conditions, as well as minimize environmental impacts, in terms of the rational use of resources, reduction of waste generation, among other aspects (WE FORUM, 2016).

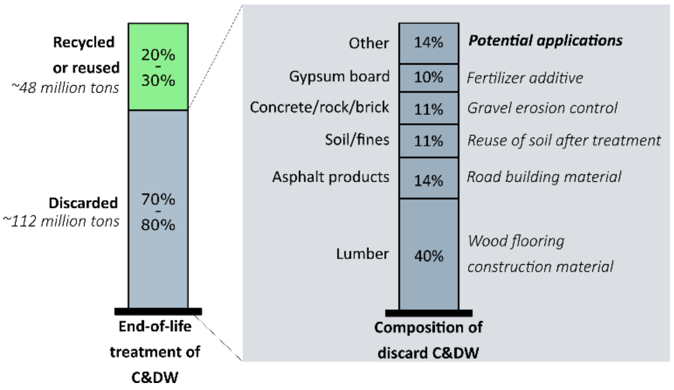
Apart from the need of investment and technical capacity, one of the main barriers to the application of novel tools is the conservative approach of the construction industry. In comparison to many other industries, the construction has been slow in the technological development, not presenting sudden changes in its processes and in efficiency improvements. Considering the representativeness of this sector, it is important to apply new technologies of the digital space, since a small improvement can bring substantial benefits to the society. For example, 1% rise in construction productivity worldwide could save $ 100 billion a year (WE FORUM, 2016).

In the environmental context, the construction industry is responsible for huge impacts, mainly in terms of natural resources consumption, air pollution and solid waste generation (BRIBIÁN; CAPILLA; USÓN, 2011; YUAN *et al*., 2012; UNEP GEAS, 2014; VITALE *et al*., 2017). This sector is the largest global consumer of resources and raw materials (about 3 billion tons of raw materials per year are used to manufacture building products worldwide), and constructed objects account for 25-40% of the world’s total carbon emissions (WE FORUM, 2016; 2018).

With regard to the construction and demolition wastes (C&DW), it has been estimated a generation of 858 million tons in Europe in 2014 (representing 34.7% of the total waste generated) (EUROSTAT, 2017) and, an annual generation of 2,360 million tons in China, between 2003 and 2013 (ZHENG *et al*., 2017). In the United States, this type of waste accounts for 26% of the total non-industrial solid waste produced, and only 20 to 30% of all C&DW is reused or recycled (Figure 1), mainly because buildings are designed and built in a way that does not enable the selective demolition, which would allow the recovery of large amounts of recyclable materials, such as steel, wood and concrete (ELLEN MACARTHUR FOUNDATION, 2013).

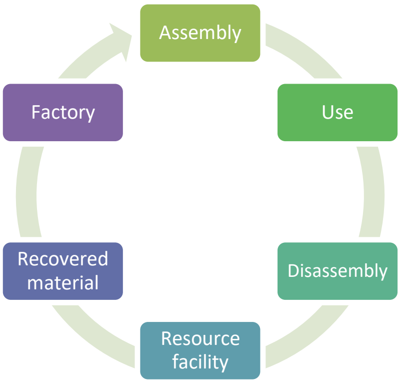
The high C&DW generation represents a significant loss of resources around the world. Therefore, to make the construction industry more sustainable, it is important to consider the principles of closed-loop circular design (Figure 2), and incorporate them into their product portfolio and business models (ELLEN MACARTHUR FOUNDATION, 2013; WE FORUM, 2016). As an example, since 2015 there is a project named "Buildings as Material Banks" (BAMB), composed by 15 partners from 7 European countries, which are working to enable a systemic shift in the building sector. Two main tools have been developed to increase materials recovery and reuse: "Materials Passports" is a database on product/materials characteristics and, "Reversible Building Design" is a source of information on how dismantle buildings while preserving the quality of the components for further use (APELMAN; HENROTAY; CORNET, 2016; BAMB, 2018).

Figure 1. Data on C&DW generated and recovered in United States.



Source: adapted from Ellen MacArthur Foundation (2013).

Figure 2. Circular economy principles in the construction value chain.



Source: Dobson (2017).

2.1 CONSTRUCTION AND DEMOLITION WASTE

In Brazil, the construction and demolition waste is defined as those arising from the construction, renovation and demolition of civil works, including those resulting from the preparation and excavation of land (BRASIL, 2002; 2010). C&DW has been classified into four classes, in order to enable their proper management (Table 1). In addition, Chapter 17 of Brazilian Solid Waste List (BRASIL, 2012b) has been used for a more detailed classification.

Table 1. Brazilian classification of construction and demolition waste.

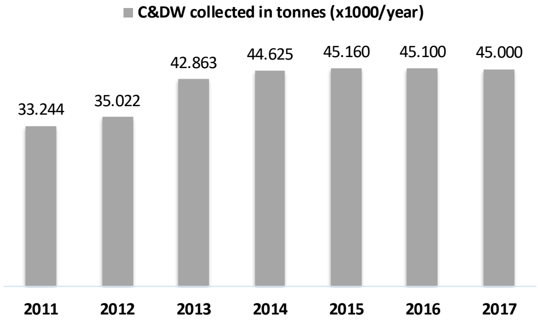
Class	Definition	Examples
A	Materials that may be reused or recycled as aggregates	Ceramic components (bricks, blocks, tiles, etc.), mortar, concrete, soil from earthworks, and others
B	Other recyclable materials	Plastic, paper, cardboard, metals, glass, wood, empty containers of paints[1] and gypsum
C	Materials for which economically feasible recycling technologies do not exist	Cardboard packaging containing cementitious materials, sealants, neoprene plastics, fiber reinforced plastics, and others[2]
D	Hazardous wastes from the construction processes	Paints, solvents, oils, resins, and others

Notes: [1]Empty containers of paints should contain only a dry film of paint, without the accumulation of liquid paint residue (BRASIL, 2015). [2]Examples based on São Paulo (2014a). Sources: Brasil (2002; 2004; 2011 and 2015).

In accordance with the last report published by ABRELPE (Brazilian Association of Public Cleaning and Special Waste Companies), the Brazilian municipalities collected about 45 million tonnes of C&DW in 2017, which represent a decrease of 0.1% compared to 2016. This report has been elaborated based on data from a questionnaire answered by the municipalities, and the results comprise an estimate about the C&DW collected by the municipalities mainly from illegal disposal, not including C&DW from demolitions and constructions collected by private companies (ABRELPE, 2018).

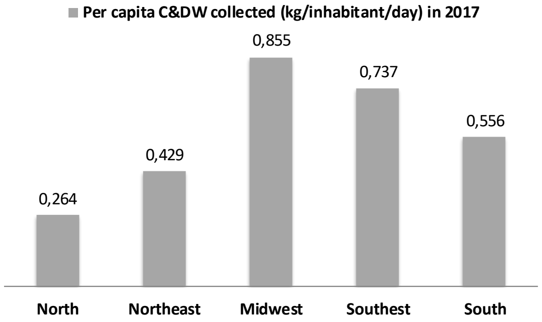
Figure 3 shows the C&DW collected from 2011 to 2017. The increase between 2012 and 2013 may be justified by the implementation of economic measures, such as tax reduction of some construction materials, expansion of housing loans, especially the “My Home – My Life” Program, and the increase of resources provided by the Growth Acceleration Program (MONTEIRO FILHA; COSTA; ROCHA, 2010). In recent years, the C&DW generation is stable as consequence of the economic retraction. Figure 4 highlights the difference of per capita C&DW collected among the Brazilian regions in 2017, which is related to economic development.

Figure 3. C&DW collected by Brazilian municipalities from 2011 to 2016.



Sources: Abrelpe (2012; 2013; 2014; 2015; 2016; 2017; 2018).

Figure 4. Per capita C&DW collected by Brazilian municipalities in 2017.



Source: Abrelpe (2018).

The last version of “Municipal Solid Waste Management Report” (SNIS, 2018) comprises data on 3,670 municipalities, which represents 65.9% of the total and 84% of the urban population. Table 2 lists the quantity of C&DW collected by (i) the municipalities; (ii) the private transport services contracted by the generators and, (iii) the generators with their own cars, small trucks or other devices. There is an inconsistency between both documents (ABRELPE and SNIS), since they comprise data from a sample of Brazilian municipalities, gathered by different methodologies, along with the lack of reliable data about C&DW management.

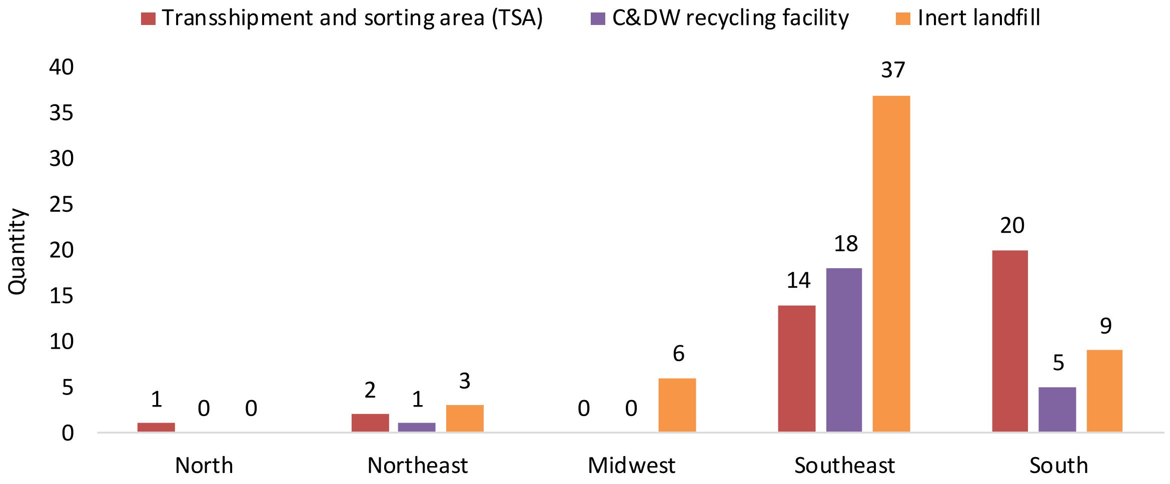
Table 2. Quantity of C&DW collected by the municipalities (tonnes), private service and own generators in 2016, and the representativeness of São Paulo State (%).

	Municipalities	**Private service**	**C&DW generator**	**Total**
Brazil (t)	8,556,036	8,105,334	815,026	17,476,396
São Paulo State (%)	20	41	25	30

Source: SNIS (2018).

Figure 5 shows the type and quantity of infrastructures used by Brazilian municipalities, which are managed by public sector (60%), private sector (29%), intermunicipal consortium (2%) and other (9%). In addition, Table 3 lists the quantity of C&DW received in each infrastructure in 2016. The total amount of C&DW received in the infrastructures represents 22% of the total shown in Table 2, which means an inefficiency in the control of C&DW flows by the municipalities or, it suggests that about 80% of the C&DW generated is (i) sent to not registered infrastructures, (ii) reused directly after generation – especially excavation soil materials, (iii) sent to sanitary landfills, dump sites, or other illegal disposal areas.

Figure 5. C&DW management infrastructures used by the Brazilian municipalities in 2016.



Source: SNIS (2018).

Table 3. Quantity of C&DW(tonnes) received in the infrastructures used by the Brazilian municipalities in 2016.

Infrastructure	**North**	**Northeast**	**Southeast**	**South**	**Midwest**	**Total**
Sorting area	0	138,240	62,507	274,097	0	**474,844**
Recycling facility	0	0	702,778	124,161	0	**826,939**
Inert landfill	0	116,447	1,946,457	92,350	485,340	**2,640,594**
Total	**0**	**254,687**	**2,711,742**	**490,608**	**485,340**	**3,942,377**

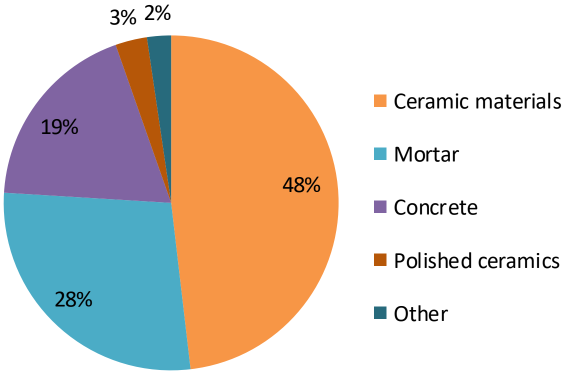
Source: SNIS (2018).

The C&DW composition and quantity are related to the raw materials, technology used in the construction sector and waste management practices. Thus C&DW composition is influenced by regional parameters and varies over time, due to the characterisation method, period and source of sample - construction site, different phases of construction, renovation, demolition, recycling facility or landfill (JOHN, 2001).

The analysis of the Solid Waste Management Plans of municipalities located in the PCJ Watershed (São Paulo State), carried out in 2016, revealed that only twelve of the municipalities (about 20%) performed a characterisation of the C&DW (Amparo, Atibaia, Limeira, Monte Alegre do Sul, Morungaba, Pedra Bela, Pinhalzinho, Santo Antônio de Posse, Serra Negra, Socorro, Torrinha and Tuiuti). This suggests that most municipalities have elaborated their waste management plans based on literature data. The average C&DW composition based on data of the twelve municipalities is 65% of C&DW Class A, 23% of land/soil, 4% of wood, 4% of recyclable wastes (metal, plastic, glass, cardboard) and 4% of others.

Figures 6 to 11 show some C&DW compositions based on samples from different Brazilian regions, the methodologies used for the characterisation are described in the figures.

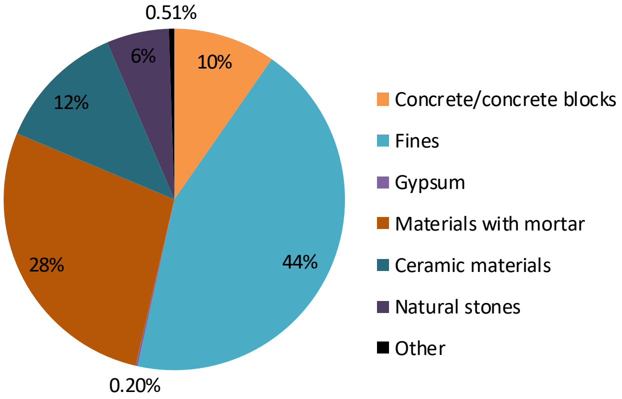
Figure 6. Gravimetric composition of C&DW generated in the demolition of a school in Maceió (Alagoas State, Northeast region).



Source: Vieira (2003).

- Sample: demolition of a school.
- Previous sorting of impurities, crushing and sieving.
- Determination of the composition of the large size materials.
- Manual characterisation of two samples of 12 kg each.

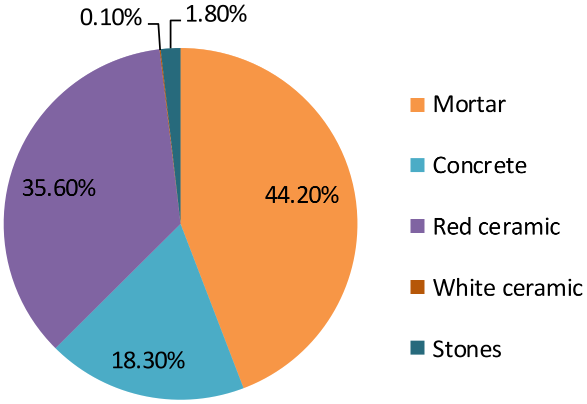
Figure 7. Gravimetric composition of C&DW generated at construction sites in Brasília (Distrito Federal, Midwest region).



Source: Rocha (2006).

- Sample: 14 construction sites of civil works in different phases.
- C&DW collected directly in the skips.
- Method used to determine the composition manually: washing (fine fraction removal); drying in an oven; manual sorting and weighing.

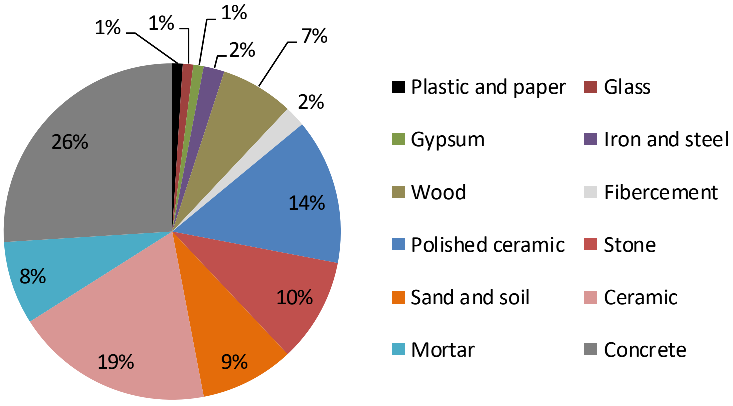
Figure 8. Gravimetric composition of C&DW disposed of in an inert landfill in Porto Alegre (Rio Grande Sul State, South region).



Source: Lovato (2007).

- Sample: inert landfill.
- Manual characterisation.
- Fractions not considered in the composition: impurities (wood, metal, gypsum, plastic and asbestos) and fines (material with size < 4.8 mm, containing organic matter and clay soils).

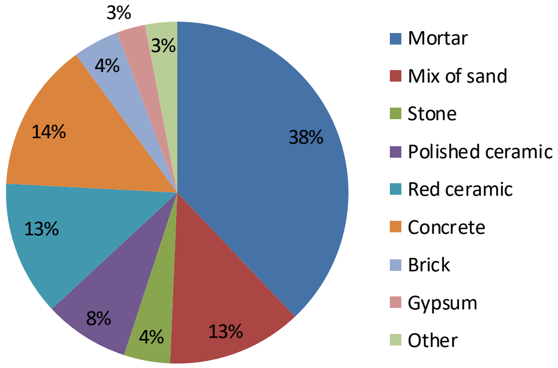
Figure 9. Gravimetric composition of C&DW disposed of in inert landfills in São Carlos (State of São Paulo, Southeast region).



- Sample: municipal inert landfills.
- Manual characterisation: sorting and weighing of C&DW from three different skips.

Source: Marques Neto and Schalch (2010).

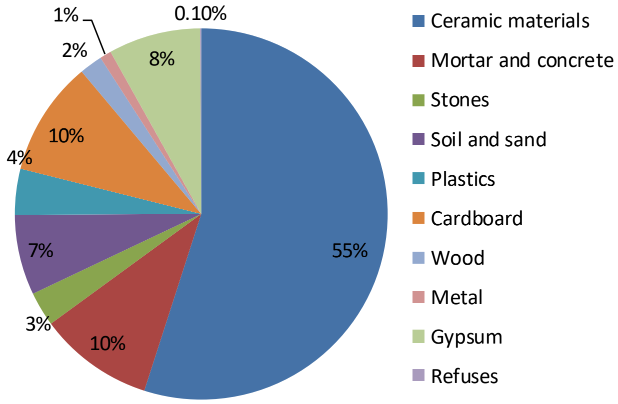
Figure 10. Gravimetric composition of C&DW disposed in an inert landfill in Fortaleza (Ceará State, Northeast region).



- Sample: inert landfill.
- Sampling was carried out twice a week, during three non-consecutive months, during a year.
- Manual characterisation.
- Other fraction comprises: residues of glass, iron, bitumen, yard wastes, wood, paper, plastic, paint, aluminium, impurities, asbestos, styrofoam and organic matter.

Source: Oliveira *et al.* (2011).

Figure 11. Gravimetric composition of C&DW generated in constructions of low income housings in São Luís (Maranhão State, Northeast region).



- Sample: construction sites of low income housings of “My Home – My Life” Program.
- Houses of 42m².
- Manual characterisation.

Source: Córdoba; Martins Filho and Lino (2014).

The C&DW gravimetric compositions shown in the previous figures reveal the predominance of C&DW Class A, also named as mineral fraction, which comprises from 75% to 100% of the C&DW, regardless of source and/or characterisation methodology used. The C&DW characterisation adopted by the Solid Waste Management Plan of São Paulo State has a similar characteristic, with 95% of C&DW Class A (32% of soil, 30% of ceramic materials, 25% of mortar and 8% of concrete) and 5% of other materials (SÃO PAULO, 2014b).

The Resolutions nº 307/2002 and nº 448/2012 of CONAMA (Brazilian Council of Environment) determine that C&DW Class A, after sorting, should be primarily reused or recycled as aggregates. If these practices are not possible, the waste can be sent to landfill for C&DW Class A, which aim to reserve the material for further uses or for the future use of the area (BRASIL, 2002; 2012).

Usually, the landfill of C&DW Class A, also known as inert landfill, does not have lining and leachate drainage systems. Therefore, if the C&DW Class A is mixed with other types of C&DW (Class B, C and D) and/or with wastes from other sources (such as organic matter), it may cause contamination of the landfill areas, as well as jeopardize recycling, due to the potential contamination of the recycled aggregates (RA) (CÓRDOBA; SCHALCH, 2015).

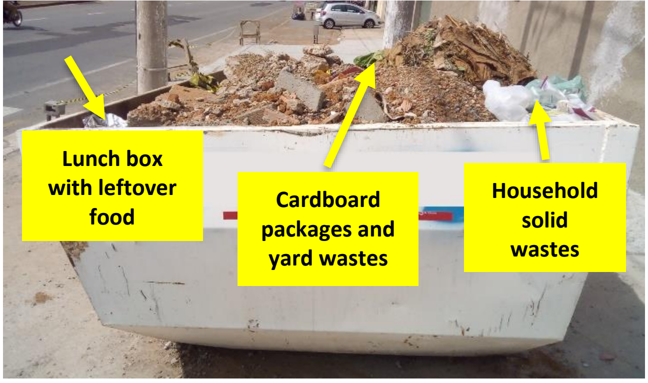
2.2 CONSTRUCTION AND DEMOLITION WASTE MANAGEMENT SYSTEMS

The C&DW collection and transport can be performed by public service, private companies or by the generator itself (SÃO PAULO, 2014a). Usually, the collection system comprises skip bins from 3 m³ to 5 m³ capacity or roll off containers from 15 m³ to 40 m³ capacity (SÃO PAULO; SINDUSCON, 2012).

The collection and transport companies have an important role for the C&DW management, since they are responsible for the proper destination of the C&DW in TSA, recycling facilities or landfills. Moreover, these companies should provide instructions for the generators about the type of waste that can be stored into the skip bins, in order to avoid mixtures of C&DW with another wastes.

Most municipalities have established regulations for proper use of skip bins, considering traffic safety, environmental and public health aspects. In order to avoid the mixture of C&DW with other types of waste, some municipalities have recommended that the skip bins remain inside of the construction site, and only if it is not possible, the skip bin can remain on the sidewalk or street during few days. The use of a coverage in the skip bins would be a solution to avoid accumulation of water and inadequate disposal of waste that can be thrown by the people who pass through the streets. However, most of the skip bins currently used do not have coverage (Figures 12 and 13) (ROSADO; PENTEADO, 2018a).

Figure 12. Skip bin with C&DW Class A and other types of wastes.



Source: Author (2018).

Figure 13. Skip bin with amount of C&DW above the allowed.

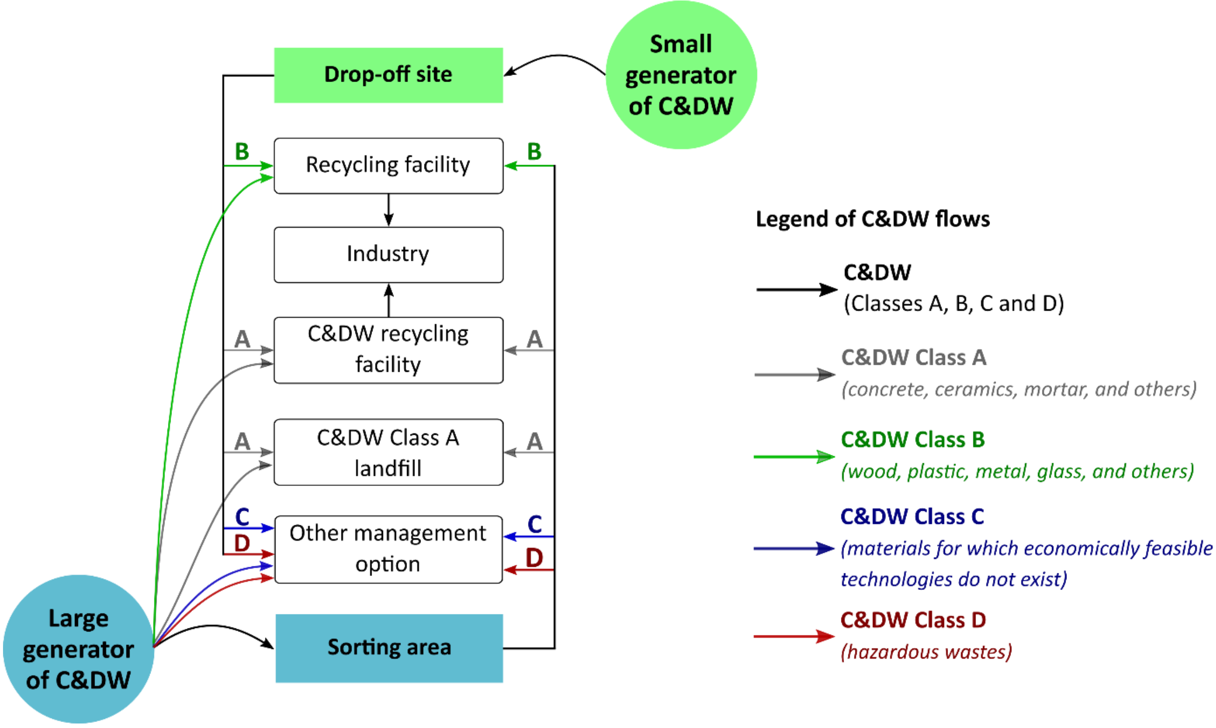
Source: Author (2017).

Another strategy adopted to reduce the mixture of C&DW with other types of waste is the increase of landfill taxes. For example, in the public landfill of Limeira, the disposal tax for a skip bin containing only C&DW is R$ 15/m³, while for a skip bin containing C&DW mixed with other type of waste it is R$ 110/m³ (LIMEIRA, 2018).

The C&DW generator, the transport company and the responsible for the final destination (TSA, recycling facility and landfill) share responsibility for the C&DW management, if any of them perform an illegal disposal, they may be fined by the public authorities (SÃO PAULO; SINDUSCON, 2012). The control of the C&DW flow must be carried out by means of the Waste Transport Control (WTC), that is a document issued in three copies: one for the generator, another for the transport company and the last one for the final destination. Each of the three parties must retain the copy, for further verification, if necessary.

Figure 14 presents the current options for the management of C&DW generated by small and large generators in the Brazilian municipalities. Drop-off sites have been used to eliminate the illegal disposal of C&DW from small constructions, renovations or demolitions. In this way, the municipalities install these infrastructures in areas with high frequency of illegal disposal. It is important to highlight that the proper operation, periodic inspection and environmental awareness campaigns are essential factors to ensure that the drop-off sites effectively improve waste management, otherwise such sites may become a dumping site (SINDUSCON-SP, 2015).

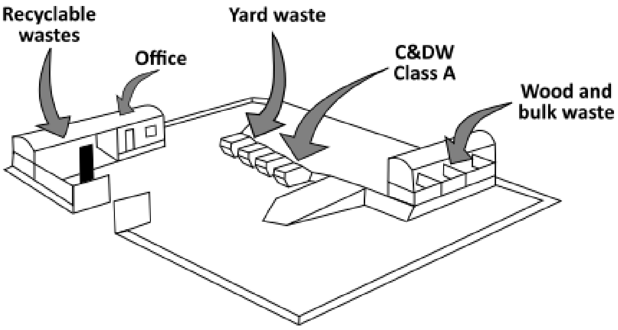
Figure 14. Recommended flow for the C&DW management generated by small and large generators in the Brazilian municipalities.



Source: adapted from São Paulo State (2014a).

The drop-off sites can receive C&DW, yard wastes, recyclable wastes and bulk waste (not removed by the municipal public collection, such as furniture and another unused household equipments) free of charge. The daily quantities vary from 1 to 2 tonnes per inhabitant; for higher quantities, the generator must contract a transport company to send the waste to sorting areas, recycling facilities or landfills. Figure 15 shows a common infrastructure of a drop-off site used by Brazilian municipalities, and Figure 16 shows a drop-off site located in Limeira, São Paulo State. (ROSADO; PENTEADO, 2018b).

Figure 15. Infrastructure of a drop-off site.



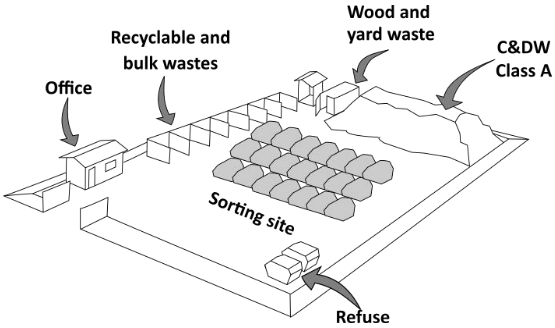
Source: adapted from Pinto and González (2005).

Figure 16. Drop-off site located in Limeira, São Paulo State.

Source: Author (2016).

Sorting areas are used to receive larger quantities of C&DW and bulk waste, for sorting, temporary storage of the sorted materials, eventual transformation and subsequent removal for recycling or final disposal (Figures 17 and 18). The layout and operation must follow the Brazilian standard NBR 15.112:2004 (ABNT, 2004c). Unlike the drop-off sites, the sorting area must issue the WTC. In the São Paulo State, if the sorting area also performs the C&DW recycling, an environmental license from the State Environmental Agency (CETESB) is necessary.

Figure 17. Infrastructure of sorting area.



Source: adapted from Pinto and González (2005).

Figure 18. Sorting area located in Campinas, São Paulo State.

Source: Author (2016).

C&DW Class A can be sent to stationary recycling facilities (Figure 19) and/or to mobile recycling facilities (Figure 20) for processing it into recycled aggregates. These facilities should be installed and operated in accordance with NBR 15.114 (ABNT, 2004d). According to ABRECON (2015), there are about 310 C&DW recycling facilities (74% stationary, 21% mobile and 5% semi-mobile) in Brazil, and 54% of them are located in São Paulo State.

Figure 19. Stationary C&DW recycling facility located in São Paulo State.

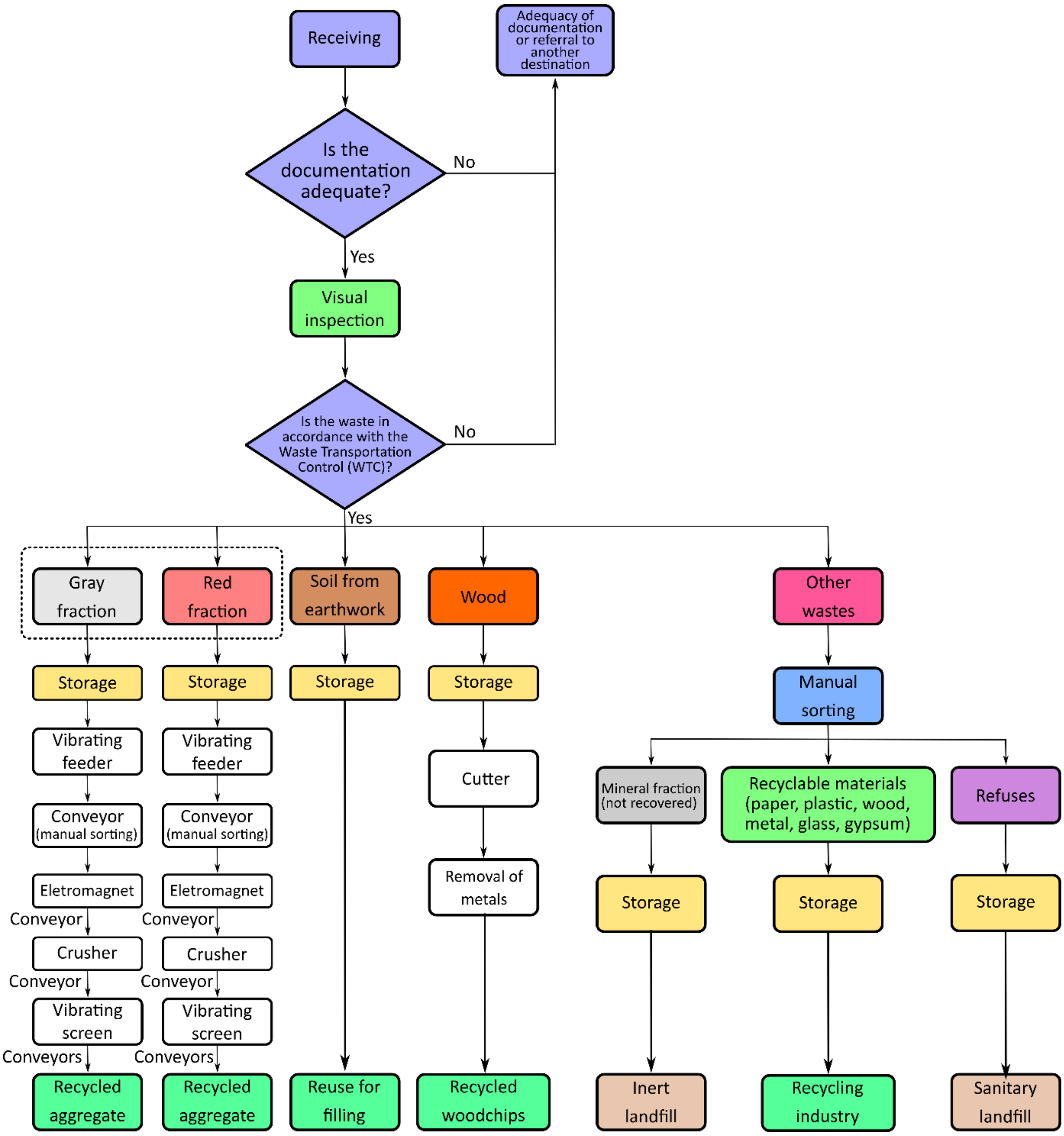
Source: Author (2016).

Figure 20. Mobile C&DW recycling facility located in São Paulo State.

Source: Author (2016).

Figure 21 shows the common process flow diagram of C&DW recycling. Firstly, the C&DW is sorted to remove plastics, wood, paper, cardboard, metal and other waste materials. Typically, this step is performed manually and, in case of existing heavy materials, a wheel loader is used. After that, the C&DW Class A is separated into three fractions: gray fraction (composed by concrete, mortar, stones), red fraction (composed by ceramic, bricks, tiles) and others (containing C&DW class A mixed with other types of wastes). Some recycling facilities do not separate the gray and red fraction.

Figure 21. C&DW Class A recycling process.



Source: Author (2019)

The gray fraction recycling produces the “recycled concrete aggregate” (composed of at least 90% by mass of cement-based fragments and stones), while the red fraction recycling produces the “recycled mixed aggregate” (composed of less than 90% by mass of cement-based fragments and stones). Both aggregates can be used as base and sub-base material in paving roads, and in manufacturing of concrete without structural function. The procedures for the use of recycled aggregates are regulated by the standards NBR 15.115 and NBR 15.116 (ABNT, 2004a; 2004b).

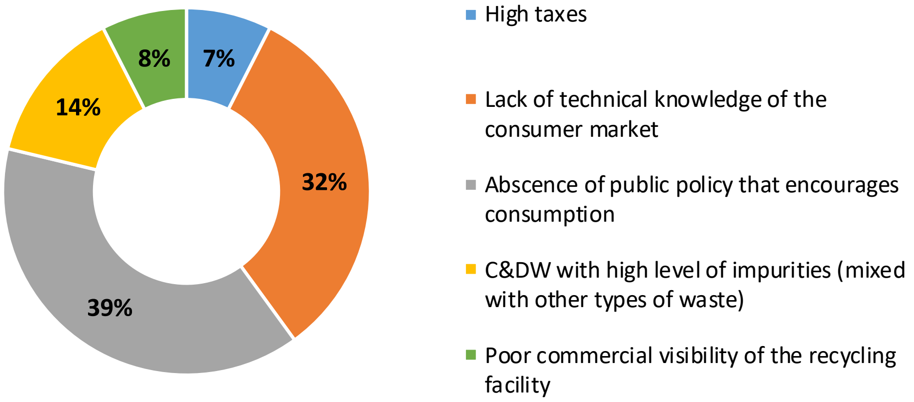
After sorting, the mixed C&DW is transferred to a vibrating feeder by a wheel loader, where the excavated soil and other fine materials are separated in a grate, and sold for different uses, mainly for environmental reclamation and filling works. The C&DW follows through a conveyor belt where small fractions of other recyclables materials are manually sorted, such as (i) wood – cut into chips and sold as biomass fuel; (ii) ferrous metals – removed by an electromagnet and sold as metal scraps; (iii) paper/cardboard, plastics and non-ferrous metals – sent to recycling industries and, (iv) refuses - sent to a sanitary landfill (organic and non-inert wastes) or to an inert landfill (mineral fraction). In some facilities, air blowers are used to improve the removal of lightweight materials such as paper and plastics.

In the next step, the C&DW passes through a crusher (jaw crusher or impact crusher), if there is market demand for a material with a wide particle size range, the obtained aggregate is sold directly; if not, the material is screened and different particle size ranges of aggregates are produced. There is a water sprinkler, located nearby to the crusher, which minimizes dust emissions. The recycled aggregates obtained are stored in open-air piles, according to type (concrete or mixed) and particle size range.

In general, the production of recycled aggregate is simpler than the production of natural aggregate, considering that in some cases, the last requires the extraction of sand and basalt for example. According to Menezes, Pontes and Afonso (2011) the price of recycled aggregates can be reduced up to 80%, compared to natural aggregates. However, John and Agopyan (2000) pointed out that the distances between the C&DW generation and the recycling facilities are the most critical aspects, since this factor directly affects the competitiveness of the recycled aggregate. Thus, it is important that C&DW recycling facilities are located as close as possible to the generation site, but, in some cases, there may be restrictions related to environmental licensing, urban zoning and even opposition of local residents (SÃO PAULO, 2014a).

Figure 22 shows the main factors that hind the marketing of recycled aggregates, according to a survey carried out in 105 C&DW recycling facilities located in Brazil (ABRECON, 2015). The absence of public policies encouraging the use of recycled aggregates and the lack of technical knowledge on the aggregates properties by the potential consumers, are the first and second factors, respectively. The third most important factor is related to the resistance of recycled aggregates use, especially due to the lack of quality assurance, which is associated to the variability in the C&DW composition. The fourth factor is related to the difficulties faced by the recycling facilities in order to make their products appealing to the consumers, and it is partially relataled to the lack of public policies and technical and marketing training for the facilities managers. Finally, the high taxes of the recycled aggregates, which are unfairly similar to those of natural aggregates appear as the last factor. According to Miranda (2005), this factors could be overcomed with a more effective participation of the public sector, by supporting the recycled aggregate consumption and by consuming it in the public construction and infrastructure works.

Figure 22. Factors related to the challenges of selling recycled aggregates.



Source: ABRECON (2015).

If it is not possible to send the C&DW Class A to a TSA or recycling facility, this waste can be sent to specific landfills. The C&DW disposed in this type of landfill must be free of other types of waste in order to allow its future use or future use of the area, without any risk for the public health and the environment (BRASIL, 2012a).

In practice, the operation of a landfill of C&DW Class A requires an efficient control, as it is common to find C&DW Class A mixed with other types of waste in the skip bins, as highlighted in Figures 23 and 24. In some cases, the generator stores the mixed waste in the lower part of the skip bin and fill the top (more visible) only with C&DW Class A. Then, the operator will discover the irregularity only after the waste has been disposed in the landfill, and often, the problem cannot be corrected. (ROSADO; PENTEADO, 2018a).

Figure 23. Landfill for C&DW Class A and inert wastes located in Limeira, São Paulo State.

Source: Author (2018).

Figure 24. Wastes disposed in the landfill for C&DW Class A and inert wastes (before compaction) located in Limeira, São Paulo State.

Source: Author (2018).

According to the Brazilian standard (ABNT, 2004e), landfills for C&DW Class A do not need lining and leachate collection systems, however, groundwater and surface water monitoring is required for landfills with areas larger than 10,000 m² and disposal volume capacity that exceeds10,000 m³. There are no guidelines establishing permeability coefficients for soil or geomembrane liners, as well as there is no requirement for the installation of leachate drainage systems.

In the São Paulo State, the inert waste and C&DW Class A landfills should accomplish the ABNT 15.113 (ABNT, 2004e) requirements. However, if the total capacity exceeds 500,000 m³ and/or the landfill receives more than 300 m³ of waste per day, an additional environmental study is required, including soil and groundwater monitoring according the parameters specified in the environmental regulation (CETESB, 2019). The Environmental Agency also determines three conditions that do not require environmental licensing: (i) fill works of an area up to 1,000 m² using a volume up to 1,000 m³; (ii) areas of reception and storage of excavated soil for use in fill works, and (iii) areas of C&DW sorting and storage (CETESB, 2010).

The main management practice adopted for C&DW is still the landfilling (67%), despite the existence of several studies that prove the technical, economic and environmental viability of the C&DW recycling (CARNEIRO *et al*., 2001; FERNANDES, 2004; MOTTA, 2005; LEITE *et al*., 2011). Therefore, it is essential to create specific laws and regulations encouraging the use of recycled aggregates; formalize environmental education programs at the construction sites and develop new technologies for the C&DW recycling sector.

2.3 BRAZILIAN REGULATIONS ON CONSTRUCTION AND DEMOLITION WASTE

Table 4 lists the main regulations applied to Brazil (Federal Laws and CONAMA Resolutions) and specific regulations applied to São Paulo State, both have been established with the purpose of defining guidelines, objectives and instruments for the integrated management of solid wastes in general and, in some cases, specifically for the C&DW management.

Table 4. Regulations about solid waste in general and construction and demolition waste.

Year	Legislation
1998	**Federal Law nº 9,605:** imposes criminal and administrative sanctions derived from conducts and activities that are harmful to the environment.
2001	**Federal Law nº 10,257:** establishes rules of public order and social interest that regulate the use of urban property for the collective good, security and well-being of citizens, as well as environmental balance.
2002	**CONAMA Resolution nº 307:** establishes the guidelines, criteria and procedures for the C&DW management.
2004	**CONAMA Resolution nº 348:** amends the Resolution nº 307, including asbestos in the Class D (hazardous waste).
2006	**São Paulo State Law nº 12,300:** establishes the Solid Waste Policy of São Paulo State.
2009	**São Paulo State Decree nº 54,645:** regulates the Law nº 12,300.
2007	**Federal Law nº 11,445:** establishes the national guidelines for basic sanitation.
2010	**Decree nº 7,217:** regulates the Law nº 11,445.
2010	**Federal Law nº 12,305:** establishes the National Solid Waste Policy.
2010	**Decree nº 7,404:** regulates the Law nº 12,305.
2011	**CONAMA Resolution nº 431:** amends the Resolution nº 307, switching the classification of gypsum to Class B (recyclable waste).
2012	**CONAMA Resolution nº 448:** amends the Resolution nº 307, modifying nomenclatures and deadlines.
2014	**São Paulo State Decree nº 60,520:** establishes the System of Online Solid Waste Management (SIGOR).
2015	**CONAMA Resolution nº 469:** amends the Resolution nº 307, instructing that empty paint containers are considered C&DW Class B (recyclable waste).

Source: Author (2019).

CONAMA Resolution nº. 307 of 2002 is the main regulation for C&DW management, defining responsibilities for municipalities, small and large generators, transport companies and infrastructures, also including the guidelines for reducing the environmental impacts caused by the C&DW. This Resolution was updated by Resolution nº. 348 of 2004, Resolution nº. 431 of 2011, Resolution nº. 448 of 2012 and Resolution nº. 469 of 2015, as shown in Table 4.

Based on a diagnostic about the C&DW (IPEA, 2012), the preliminary version of the National Solid Waste Plan has proposed the six goals described below (BRASIL, 2012c):

- **Goal 1:** Elimination of all illegal disposal areas.
- **Goal 2:** Disposal of C&DW Class A only into authorized landfills.
- **Goal 3:** Implementation of drop-off sites and sorting areas.
- **Goal 4:** C&DW reuse and recycling.
- **Goal 5:** Request of C&DW Management Plans from large generators, and implementation of a declaratory system to gather data from generators, transporters and management infrastructures (TSA, recycling facilities and landfills).
- **Goal 6:** Elaboration of quantitative and qualitative diagnostics of C&DW generation, collection and destination.

The deadline established for the fulfilment of the goals by all Brazilian municipalities was 2015, except for goal number 5, whose deadlines vary according to each region of the country (Table 5).

Table 5. Goals for C&DW reuse and recycling according to the National Solid Waste Plan.

Brazilian region	2015	2019	2023	2027
North	75%	100%		
Northeast	60%	80%	100%	
South	60%	80%	100%	
Southeast	50%	70%	85%	100%
Midwest	75%	100%		

Source: Brasil (2012c).

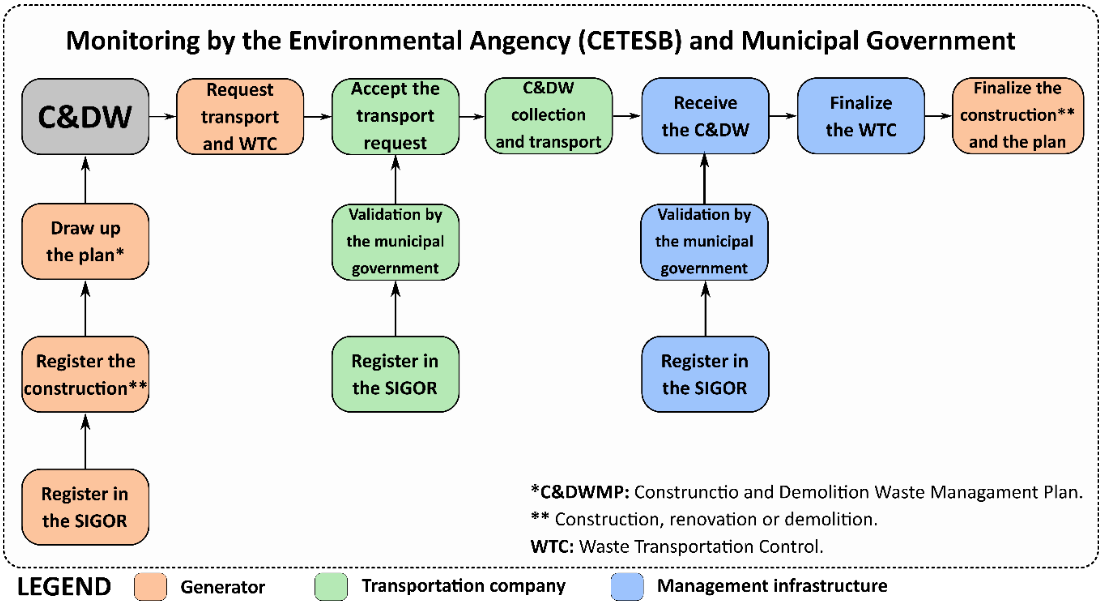
In accordance with the IBGE (2010), only 392 municipalities (about 7% of the total) have some process or initiative of C&DW reuse and/or recycling; in this way, the aforementioned goals are not consistent with the national scenario. In this sense, it is expected that these goals be reformulated, based on an inventory containing real data on the amount generated and management practices adopted by the public and private sectors.

The Solid Waste Plan of São Paulo State, published in 2014 (SÃO PAULO, 2014b), presents the following detailed goals for the C&DW management, which must be met by all municipalities until 2019: (i) elimination of all illegal disposal areas; (ii) implementation of drop-off sites, sorting areas and, if necessary, landfills for C&DW Class A; (iii) elaboration of C&DW Management Plans by large generators; (iv) promotion of measures to reduce the C&DW generation throughout the State.

In addition, the Solid Waste Plan of São Paulo State aims to implement reverse logistics, promote good practices initiatives to reduce waste generation at source and encourage the use of recyclable materials. In this sense, the targets for C&DW reuse and recycling for all municipalities located in the São Paulo Stare are: 70% in 2019; 85% in 2023 and 100% in 2025 (SÃO PAULO, 2014b).

São Paulo State has also created the System for Online Management of Solid Waste (SIGOR) in order to gather data on solid waste flows, and the C&DW was chose as the initial module. The main goal of SIGOR is to control de C&DW management, considering the generator, transport companies and management infrastructures. Figure 25 shows how the SIGOR works. According to CETESB (2018), until September 2018, only three municipalities had registered in SIGOR (Catanduva, Santos and São José do Rio Preto).

Figure 25. Operation of the System for Online Management of Solid Waste (SIGOR).



Source: adapted from São Paulo (2014a).

According to the National Solid Waste Policy and CONAMA Resolution nº. 448 of 2012, the municipalities should elaborate the C&DW Management Plan in accordance with the Municipal Solid Waste Management Plan. The C&DW Plan must comprise the guidelines for the generators (small and large), transport companies and management infrastructures.

The municipal government is responsible for managing the C&DW from small generators, whether natural person or legal entity, public or private. The definition of small generator is not provided by law, then, the municipalities usually adopt the volume of 1 to 2 m^3 of C&DW generated per day per inhabitant. Large generators, who generate more than 1 or 2 m^3 of C&DW per day, must elaborate the C&DW Management Plan (SÃO PAULO, 2014a).

2.4 STUDIES ABOUT CONSTRUCTION AND DEMOLITION WASTE MANAGEMENT

The literature review of the main studies related to C&DW management systems was based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statements, by using explicit and systematic search methods (MOHER *et al.*, 2009). The search was performed in the databases Science Direct, Web of Science, Scopus, Scielo and Brazilian Digital Library of Theses and Dissertations (BDTD), by using the keywords described in Table 6.

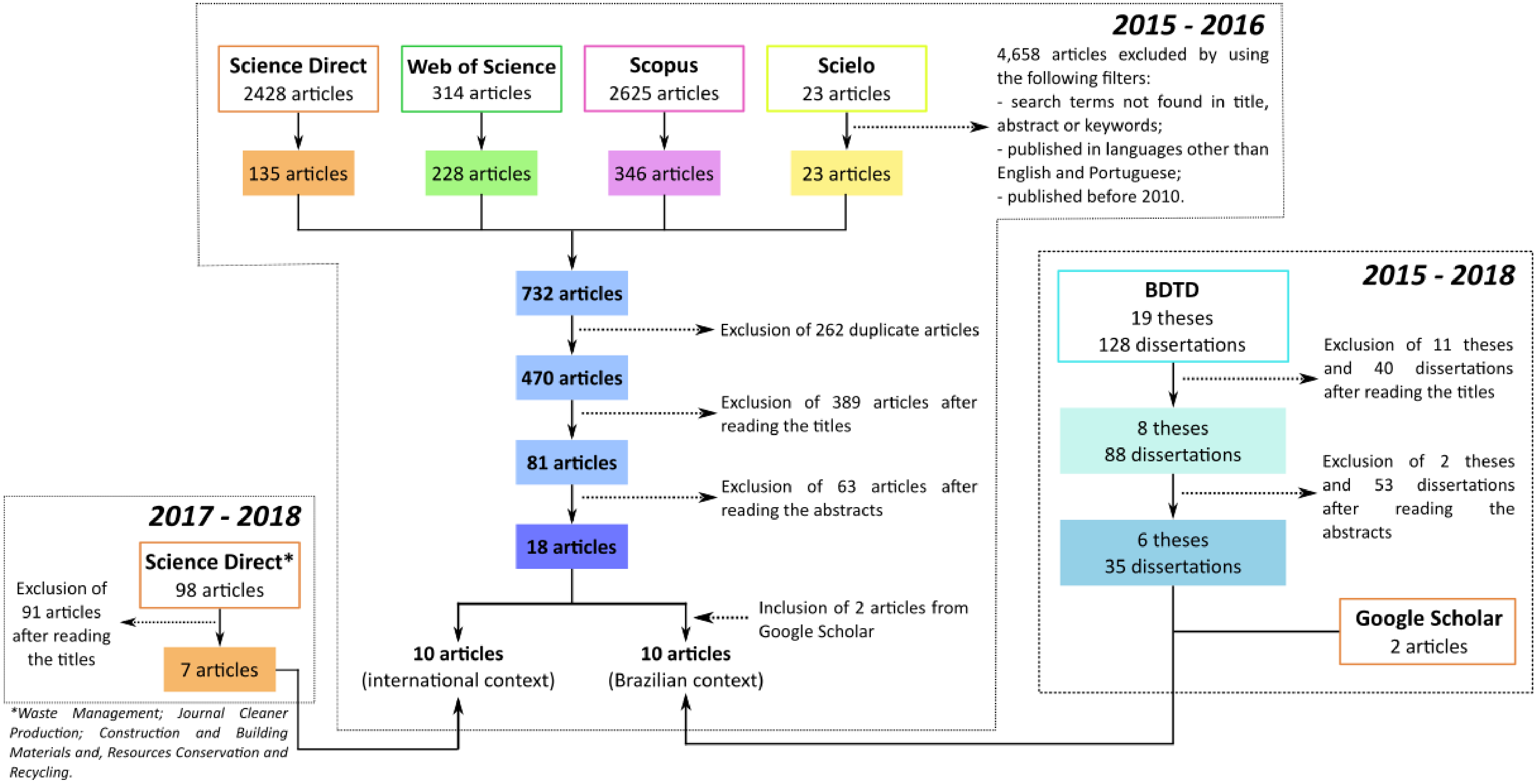
Table 6. Keywords and search strategies used in each database.

Database	Search strategies
National Scielo BDTD	(“resíduo da construção civil” OR “resíduo da construção e demolição” OR “RCC” OR “RCD”) AND (“gerenciamento”)
International Science Direct Web of Science Scopus	(“construction and demolition waste” OR “construction waste” OR “demolition waste” OR “C&DW” OR “C&DW” or “CDW”) AND (“management”)

Figure 26 shows the results of the search carried out from 2015 to 2016 (concluded in November). In total, 5,390 articles were obtained, filters were used to exclude articles without the search terms in the title, abstract or keywords, articles published in languages other than English and Portuguese and, articles published before 2010, resulting in 732 articles. After the exclusion of duplicate articles, the final result consisted of 470 articles, of which 81 were selected according to the reading of the titles. At the end, according to the reading of the abstracts, 10 articles related to the international context and 8 articles related to the Brazilian context were selected. In the Google Scholar search, two Brazilian articles were found and added in this review. The main contributions of each article are described in the sections 2.5.1 and 2.5.2, and additional information about the selected articles are listed in the Appendix A1 (Tables A1.1 and A1.2).

The search was updated in October 2018, considering only articles published in 2017 and 2018 in the main journals related to C&DW management: Waste Management, Journal of Cleaner Production, Construction and Building Materials and, Resources, Conservation and Recycling. In this search 98 articles were obtained, and after the title reading, 7 were selected. The search of theses and dissertations was carried out between 2015 and 2016 and updated in October 2018; 6 theses and 35 dissertations about C&DW management systems were selected. The discussion on the selected studies are presented in the section 2.5.2.

Figure 26. Data about the search on C&DW management carried out from 2015 to 2018.



Source: Author (2019).

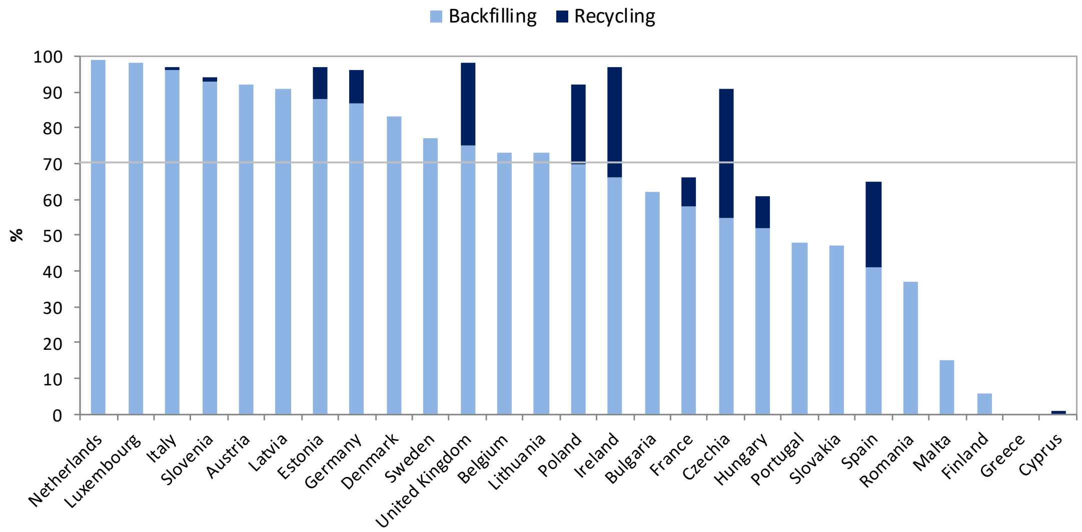
2.4.1 CONSTRUCTION AND DEMOLITION WASTE MANAGEMENT SYSTEMS – INTERNATIONAL CONTEXT

In 2014, the European countries generated more than 870 million tonnes of C&DW, which corresponds to 1,729 kg/inhabitants/year (EUROSTAT, 2017), which comprise several types of materials, including concrete, bricks, gypsum, wood, glass, metals, plastics, solvents, asbestos and excavated soil (EUROPEAN COMMISSION, 2018).

C&DW has been identified as a priority waste stream by the European Union (EU), due to its high generation rate and, reuse and recycling potential (EUROPEAN COMMISSION, 2018). In this context, one of the targets by 2020 of the Waste Framework Directive of EU (2008/98/CE), determines that the Member States should adopt measures to ensure that at least 70% (by weight) of non-hazardous C&DW[2] is sent to reuse, recycling or other practice of material recovery, including backfilling operations using waste as a substitute of other materials (EUROPEAN COMMISSION, 2008).

Despite the existence of economically viable technologies for C&DW recycling, the recycling rates varies widely (from less than 10% to more than 90%) across the EU (Figure 27). The countries with the highest recycling rates are the United Kingdom, Poland, Ireland, Czech Republic and Spain, while the others use the C&DW mainly for backfilling operations (EUROPEAN COMMISSION, 2011).

Figure 27. C&DW recovery and recycling rates in the European Union in 2011.



Source: adapted from European Commission (2011a).

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[2] Excluding naturally occurring material defined in category 17 05 04 in the list of waste (soil and stones).

Backfilling is defined as "*a recovery operation where suitable waste is used for reclamation purposes in excavated areas or for engineering purposes in landscaping and where the waste is a substitute for non-waste materials*". In this sense, it differs from recycling because the waste is not processed before the use, which means that its physicochemical properties are not modified, and, in case of necessity, the material can be used again for the original function or for other purposes (EUROPEAN COMMISSION, 2016).

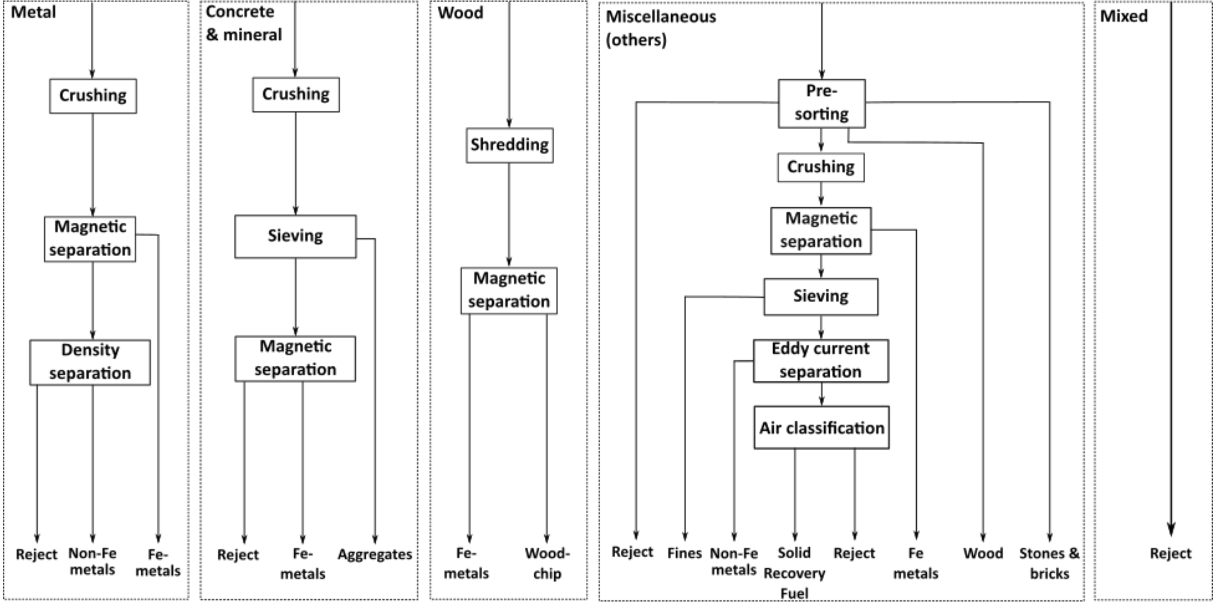
The EU members with high recycling rates have in common high taxes for waste landfilling and, strong financial incentives for the construction companies that carry out the waste sorting. On the other hand, the main factors that justify the low rates of C&DW recovering and recycling in some EU members are (i) low taxes for C&DW landfilling and reduced or non-existent fines for illegal disposal; (ii) relative low cost of natural raw materials, (iii) lack of or differences in the C&DW regulations among the countries. Usually, countries that have introduced measures to improve the waste management have achieved higher recycling rates (SÁEZ *et al.*, 2011).

Currently, the EU has technology to achieve high performing waste management systems and, municipalities, waste authorities or waste contractors willing to improve their performance. On the other hand, the heterogeneity among the EU member regarding to the C&DW management, shown in Figure 27, reveals that the construction sector still has a traditional behaviour, since the low impact of any decisions related to waste management on construction project budgets does not encourage improvement beyond the current standard practices (GÁLVEZ-MARTOS *et al*., 2018).

Design for Deconstruction (planned disassembly of buildings) allows the recovery of materials and components after the end of life of buildings, and therefore, it is a recommended strategy to reduce the generation of mixed C&DW and, consequently, minimize landfilling. Deconstruction is not a new concept in the construction industry, but its planning depends to a large extent on the proper specification of building components, to facilitate disassembly. Experts from the UK construction industry consider that the main factors that encourage the deconstruction are: stringent legislation and policy, design process and competency for deconstruction, design for material recovery, reuse and building flexibility (AKINADE *et al*., 2017).

Finland is one of the EU members with the lowest recovery rates, and the country does not carry out recycling. Dahlbo *et al*. (2015) evaluated the environmental and economic performance of the C&DW management system in this country (Figure 28), by means of three methodologies: material flow analysis, life cycle assessment and environmental life cycle costing. The current and two alternative scenarios were evaluated, considering the amount of 2 million tonnes of C&DW (not including hazardous waste), with variations in the composition (current scenario – 13,5% metal; 35% mineral; 36% wood and 15.5% others; scenario 1 – 15% metal; 20% mineral; 45% wood and 20% others and, scenario 2 – 10% metal; 50% mineral; 20% wood and 20% others).

Figure 28. C&DW management system of Finland.



Source: adapted from Dahlbo *et al.* (2015).

Although the management system of Finland presents environmental benefits and economic viability, the results indicated that a recycling rate of 70% would not be achieved, even with the changes in waste composition. One of the critical components is wood; currently, a large fraction of this material is recovered as energy generating environmental and economic benefits, but it does not increase the recycling rate. In this case, the generation rate should be reduced or technologies to recycle the low quality wood (containing nails, concrete debris, paints and other contaminants) should be developed. Mixed waste presented major contributions for the impacts of climate change, costs and recycling of materials, then it was identified the need of improving the material sorting at source, in order to reduce the volume and to obtain fractions with recycling potential, such as plastics (DAHLBO *et al*., 2015).

C&DW also represents a significant waste flow in the United States (US). It was estimated a generation of 534 million tonnes of C&DW in 2014. Concrete represents the largest portion (76%), followed by asphalt concrete (15%), asphalt shingles (3%), drywall and plasters

(3%), brick and clay tile (2%), and steel (1%). Demolition wastes accounted for more than 90% of total generation and construction for less than 10% (U.S. EPA, 2014).

The US Environmental Protection Agency (U.S. EPA) encourages the reduction, reuse and recycling practices in order to avoid the C&DW landfilling. In this context, the agency provides the following tools to improve the C&DW management: (i) manuals of C&DW reduction at generation source; (ii) selective deconstruction and material reuse guides; (iii) information on C&DW recycling and recycling facilities around the country, provided by the Construction & Demolition Recycling Association (CDRA) and, (iv) information about businesses that sale recycled materials and/or materials that can be reused (U.S. EPA, 2014).

In the US, the recycling rates also vary widely, then, an estimate-based study was developed to analyse the benefits of recycling. This study took into account the generation of 480 million tonnes of C&DW in 2012 (65% concrete, 20% mixed C&DW and 15% asphalt pavement). The results indicated that if more than 70% of the waste were recycled, 17 km² of landfill area (with a depth of 15 meters) would be avoided, with an energy saving of 85 million barrels of oil (CDRA, 2015).

Among the 17 articles selected in the literature review, 12 refer to studies about Asian countries, such as China and Hong Kong, which demonstrates that the fast economic growth and urbanization of these countries are demanding studies on C&DW management strategies.

C&DW accounts for 30% to 40% of the total amount of waste generated in China (HUANG *et al.*, 2018). In 2016, it was estimated a generation of 336 million tonnes of C&DW, composed of bricks (44%), mortar (15%), concrete (15%), wood (9%), metal (4%), packaging materials (4%) and other types of waste (6%) (SONG *et al.*, 2016). China’s government has established regulations and policies on waste management, which require improvements, since the C&DW management is still under development when compared to other wastes, such as municipal and industrial (DUAN; WANG; HUANG, 2015). For instance, no regulation related to C&DW had been established by the central government until 2005 (YUAN, 2017).

Wang *et al.* (2010) identified the critical success factors (CSF) for the implementation of C&DW on-site sorting in Shenzhen, a typical economically developed region of south China. The benefits of on-site sorting consist in the increase of reuse and recycling rates, the reduction of the transport and disposal costs, the increase of the landfills lifespan and the minimization of illegal waste disposal. The study defined the following factors as the most important to implement the on-site sorting: (i) manpower (extra labour for performing the waste sorting); (ii) market for recycled materials and, (iii) waste sortability (the better way is to separate the waste at source). Moreover, the support of the local government along with the construction companies contribute to the achievement of on-site sorting.

In addition to the challenge of improving the C&DW on-site sorting, China presents low recycling rates. According to an online survey (JIN *et al*., 2017) answered by 77 professionals with experience in C&DW management, landfilling is the main management option (70%), followed by recycling and reuse (30%) and, the remain that chose "others" (10%), specified that C&DW are mainly used as road base paving material or backfilling. The lack of demand for recycled materials was determined as the main responsible for this scenario. This research also revealed that, in addition to the role of government in the C&DW management, it is necessary to increase the C&DW recycling and reuse experience by the involved professionals, in order to provide a more positive perception of the reused/recycled products quality, while ensuring their economic viability (JIN *et al*., 2017). According to Zheng *et al*. (2017), considering the current management scenario, the potential economic profits of recycling were estimated at 201 billion US dollar in 2013, and could increase to 401 billion US dollar assuming the most optimistic scenario (with recycling rates of 99% for metal scraps and 95% for the mineral fraction).

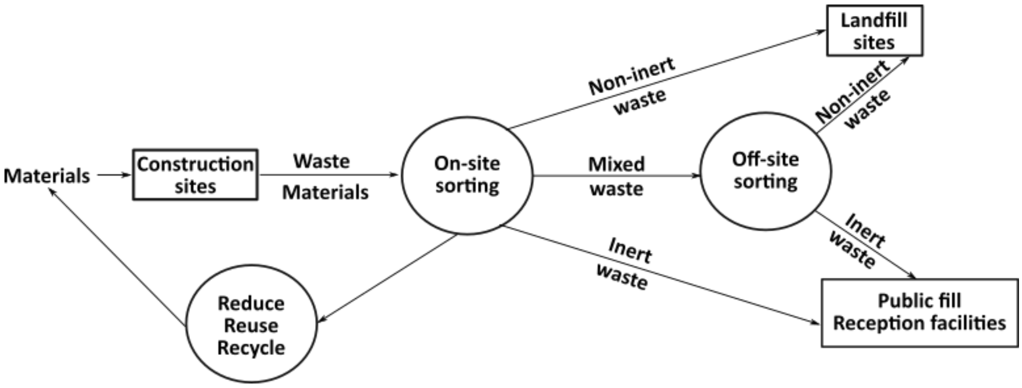
Huang *et al*. (2018) conducted an analysis of the policies and management practices through 3R principles (reduction, reuse and recycle) and the results revealed the following barriers:

- Reduction: lack of building design standards, low disposal taxes and inappropriate urban planning.
- Reuse: lack of guidance for effective C&DW collection and sorting, lack of knowledge and standards for C&DW reuse, and under-developed market for reused C&DW.
- Recycling: ineffective management system, immature recycling technology, under-developed market for recycled C&DW products and immature recycling market operation.

In this context, in order to improve the current management system, taking into account the 3R principle, it was recommended to ensure the C&DW sorting at source, the adoption of innovative technologies and market models, as well as, implementation of specific economic incentives (HUANG *et al*., 2018).

In Hong Kong the C&DW is classified as inert and non-inert. The inert fraction is mainly composed of sand, bricks and concrete and is sent to public filling areas for land reclamation, while the non-inert fraction is mainly composed of bamboo, plastics, glass, wood, paper, vegetation and other organic materials, and is disposed of in landfills. Figure 29 shows the C&DW sorting performed on-site and off-site (LU; TAM, 2013).

Figure 29. C&DW management system in Hong Kong.



Source: Lu and Tam (2013).

The C&DW sorting before its final disposal, as detailed in Figure 30, has been one of the most important strategies for the C&DW minimization in Hong Kong; from 2006 to 2012, 5.11 million tonnes of C&DW were sorted. It is important to highlight that this result was achieved due to the waste taxing scheme implemented in 2006: HK$ 125/t of C&DW disposed of in landfills; HK$ 100/t of C&DW sent to the sorting facility and, HK$ 27/t of C&DW composed only by inert materials[3], which can be used for land reclamation by the public facilities (WEISHENG; HONGPING, 2012).

According to information from six construction sites, the C&DW management regulations have significantly improved C&DW on-site sorting in Hong Kong, mainly due to the aforementioned waste taxing scheme. The overall costs of the on-site sorting were not considered as the main obstacles, however, the available area in the working site and project stakeholders' attitudes are still considered as the most critical factors (YUAN; LU; HAO, 2013). Although the efforts to improve the C&DW management, illegal dumping still happens at alarming rates in the city (DUAN; WANG; HUANG, 2015).

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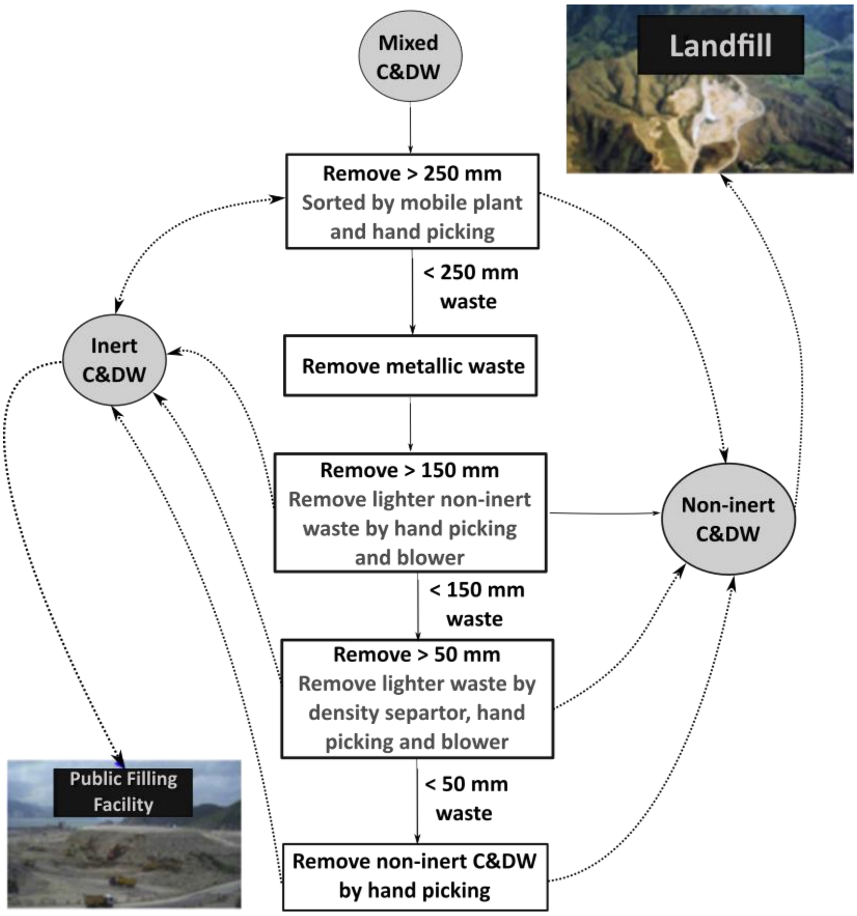
[3] 1 HK$ = R$ 0.48; 1 HK$ = US$ 0.13 and, 1 HK$ = 0.11 € (exchange rates obtained in 17th November, 2018).

Figure 30. C&DW sorting process in Hong Kong.



Source: Weisheng and Hongping (2012).

According to Ghisellini *et al.* (2018), to improve the sustainability of C&DW management in China, policies should be based on a stronger integration of economic and environmental assessment tools, such as the adoption of the waste tax scheme in Hong Kong, which has contributed to reduce the C&DW landfilling and to increase the adoption of on-site sorting and C&DW recycling.

According to a literature review of 81 articles published from 2000 and 2015, public support by means of legislation and financial investments, along with awareness programs for the citizens and practitioners involved in the C&DW management system, are the key factors to achieve efficient management in a global context. Despite the existence of a set of environmental policies worldwide, several articles have shown the inefficiency of C&DW management, mainly due to the high landfilling and low reuse and recycling rates. This scenario is justified by the deficiency of public instruments encouraging the C&DW management and, especially in developing countries, due to the inefficiency of statistical data on the C&DW flows (UMAR *et al*., 2016).

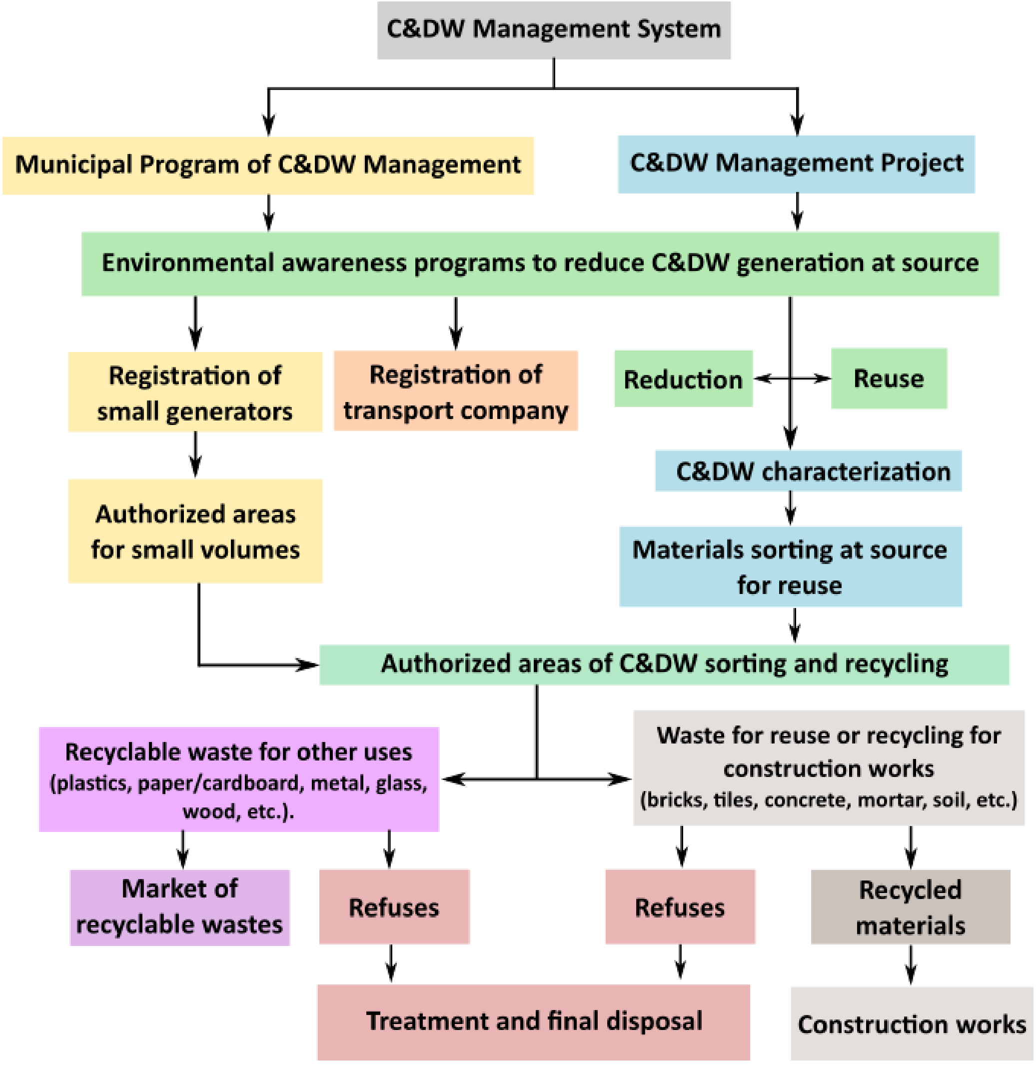
Beyond reuse and recycling practices, the concept of circular economy (CE) also emphasizes the importance of prevention and minimization practices throughout the production chain of construction. Currently, CE has been used mainly in developed countries, such as the United Kingdom, Netherlands, and other European countries. In this context, Esa, Halog and Rigamonti (2016) proposed a theorical framework for CE, using Malaysia - which generates 26,000 tonnes of C&DW/day, as a case study. Based on a literature review, this study developed a three-layer approach:

- Micro level focuses on the adoption of a cleaner production process, moving from the traditional to a modern construction method, such as the IBS (Industrialized Building System), ensuring that the waste can be monitored at source.
- Meso level encourages a waste trading system and requires that the clauses on the responsibilities of C&DW management in contracts and documents be clearly specified.
- Macro level involves the creation of monitoring and communication mechanisms to ensure the effective C&DW management, which must be implemented during the construction process. The authors pointed out the strengthening of an advanced collaborative network between industries, with incentives for reduction, reuse and recycling, as a potential solution.

2.4.2 CONSTRUCTION AND DEMOLITION WASTE MANAGEMENT SYSTEMS – BRAZILIAN CONTEXT

The selected articles about C&DW management in Brazil, published between 2010 and 2018, are mainly focused on C&DW quantification, characterisation and illegal disposal. Marques Neto and Schalch (2010) carried out a study in the municipality of São Carlos (São Paulo State), by using three parameters to quantify the C&DW: (i) waste from building works approved by the municipal government; (ii) waste collected by transport companies and, (iii) waste landfilling. In addition, this study quantified the waste generated by different types of building works and determined the rate of 137.02 kg of C&DW per constructed m^2. The characterisation data of the C&DW sent to landfills along with the analysis of 28 areas of illegal disposal allowed the authors to propose an integrated management model, which involves the local construction sector and the municipal government (Figure 31).

Figure 31. C&DW integrated management system of São Carlos, São Paulo State.



Source: adapted from Marques Neto and Schalch (2010).

Oliveira *et al.* (2011) analysed the annual C&DW generation and composition of Fortaleza (Ceará State). The data obtained from the transport companies and the municipal government indicated that the authorized areas received about 702 tonnes/day, with an average composition of 65% of mortar, concrete and ceramic materials. It was also verified that a large fraction of C&DW are sent to illegal disposal areas, and as a result, the two main irregular landfills comprise an area of approximately 26 hectares.

Silva and Fernandes (2012) studied the main environmental impacts resulting from the inefficiency of the C&DW management system in Uberaba (Minas Gerais State). After visits to the drop-off sites and areas of illegal disposal, it was verified the need of C&DW composition data and the identification of the regions that generate large volumes of waste, in order to determine the most appropriate location for a recycling facility. This study indicated that the drop-off sites are not effective for C&DW management, since some of them work as a storage area (without waste sorting), including some that are located in permanent preservation areas. After the establishment of a management system, the next step would be the recovery of the degraded areas from the C&DW illegal disposal.

Tessaro, Sá and Scremin (2012) used a software to collect the following data: (i) agents involved in the C&DW generation; (ii) agents involved in the C&DW collection and transport; (iii) areas of illegal disposal; (iv) qualitative and quantitative data on C&DW and, (v) registration of potential areas for the installation of drop-off sites, sorting areas and landfills. The data input from the municipality of Pelotas (Rio Grande do Sul State) in this software presented the following results: generation of 315.08 m³/day (1.23 kg/inhabitant/day); C&DW density of 1.28 tonnes/m³ and, about 88% of the C&DW classified as Class A (with a great potential for reuse and recycling).

Paz and Lafayette (2016) developed a software namely “C&DW Management System” (SIGERCON) based on the aforementioned software, in order to facilitate the analysis of waste management strategies in construction sites, through the use of indexes. The efficiency of the C&DW generated by constructed area index is questioned by some researchers and constructors, therefore, this study evaluated other types of indexes, such as generation of waste by working time (36.85 tonnes/month, for an average time of 35 months), or generation by numbers of floors (52.36 tonnes/floor, for an average of 27 floors). In relation to the generation rate for each stage of the building work, it was obtained the amount of 10.84 tonnes/month for the foundation stage, while for the structure stage it was obtained 22.91 tonnes/month, and in the finishing stage 47.66 tonnes/month. The use of these indexes allows to specify the C&DW amount throughout the building work, improving the proper management.

Melo, Ferreira and Costa (2013) presented the influence of the inefficiency of C&DW management on the production of recycled aggregates in the Northeast region. A large fraction of the C&DW sent to these facilities is mixed with other types of waste, which jeopardize the production of high quality recycled aggregates (mineral purity). In order to improve this scenario, this study suggests the implementation of an area for previous inspection of the C&DW composition, allowing the rejection of wastes with high contaminants content.

Lima and Cabral (2013) analysed the chemical composition of the C&DW generated in Fortaleza (Ceará State), located in the Northeast region. The results classified the C&DW as Class II-A (non-hazardous and non-inert), since some parameters, such as chrome (Cr), lead (Pb) and phosphate (SO_4^{2-}) were above to the limits specified by ABNT NBR 10.004 (ABNT, 2004f). Córdoba and Schalch (2015) carried out a similar study, in order to evaluate the potential of contamination of leachate generated at C&DW Class A landfills located in São Carlos (Southeast region), and the results have also classified the C&DW as Class II-A.

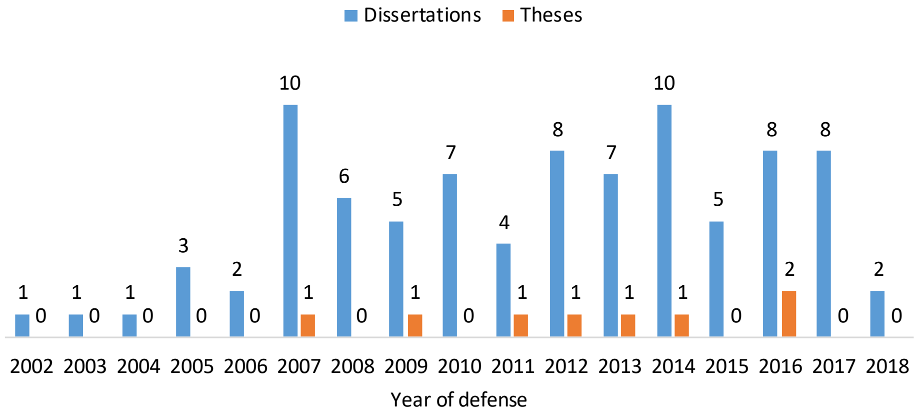
Galarza *et al*. (2015) elaborated a system dynamic model for the study of the variables involved in the production of non-structural concrete blocks with recycled aggregates in a non-governmental organization (NGO) located in Porto Alegre (Rio Grande do Sul State), focusing on economic aspects. For this case study, the C&DW is a socio-environmental alternative with economic potential. Considering the productive capacity of the facility, an average of 87,000 blocks can be produced, consuming 273 tonnes of C&DW. According to the simulations, the manufacturing process of non-structural blocks will use 1.1% of C&DW generated in Porto Alegre.

Santos, Pinto and Catunda (2015) analysed the perception of 14 construction companies about the environmental legislation in force. The results revealed that most of the companies are concerned about meeting the legal requirements, however 21% of those interviewed had no knowledge of the laws.

Rosado and Penteado (2018a) presented a participatory methodology for Municipal Management Plans for Construction and Demolition Waste elaboration, based on case study of Limeira (São Paulo State). The analysis of the steps involved in the plan elaboration showed that the union of efforts and knowledge resulted in a plan with a detailed diagnosis of the municipality, including its peculiarities, which made possible the establishment of the goals, programs and actions in accordance with the local reality. Another study of this municipality (ROSADO; PENTEADO, 2018b) revealed the difficulties of the municipal government in dealing with the C&DW from small generators. Despite the existence of drop-off sites, a considerable amount of waste is daily disposed improperly, even in areas close to the drop-off sites, confirming the need of effective monitoring programs, environmental communication and cultural change of the citizens.

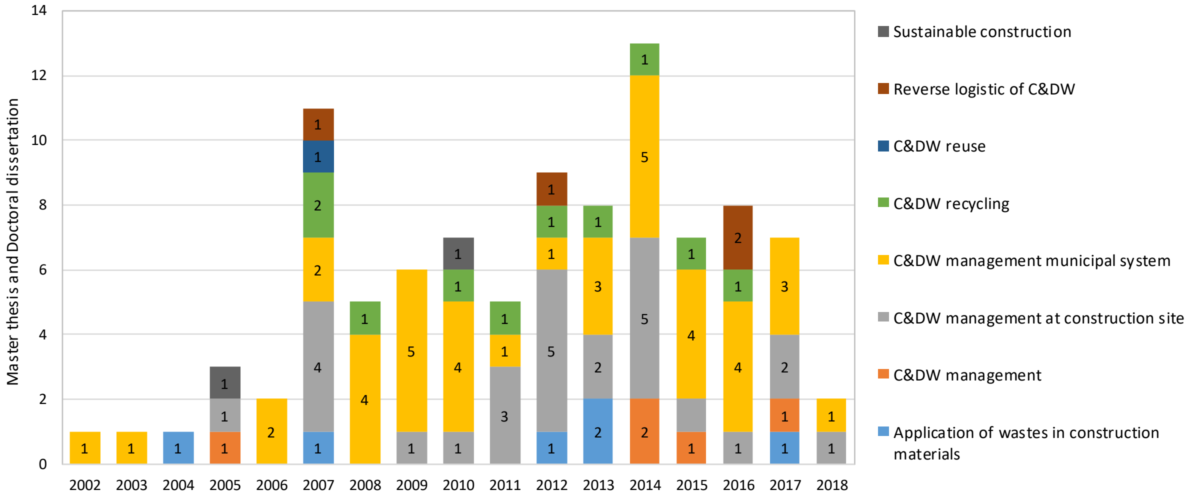
Figure 32 shows the distribution over the years, of dissertations and theses selected in the literature review carried out between 2015 and 2018, and Figure 33 presents the classification according to the main topic of the research. The main objectives of the 6 theses and 35 dissertations about C&DW management systems are detailed in Appendix A (Tables A1.3 and A1.4). The studies focused on the evaluation of the quality and use of the recycled aggregates were not included in this literature review, because they are more close related to materials sciences than waste management.

Figure 32. Dissertations and theses about C&DW management.



Source: Author (2019).

Figure 33. Classification of the main topics of the dissertations and thesis selected from the BDTD in 2018.



Source: Author (2019).

The majority of the aforementioned studies aim to provide a set of data on C&DW generation and composition of a specific Brazilian region. The number of this type of study has increased after the publication of CONAMA Resolution nº. 307 of 2002, due to the lack of reliable data available by the public government, which are necessary to evaluate the compliance of the law and to propose strategies to improve the management systems. Some studies advance in the area of software development to assist in the C&DW management by the public and private sector, and to perform economic analysis of the recycling feasibility.

The main challenge reported by the studies is the on-site sorting, which jeopardize the C&DW reuse and recycling. In this sense, economic instruments could be used to encourage the sorting practices along with environmental education programs. In relation to the small generators, the drop-off sites need better monitoring by the municipal government, to reduce the mixed waste sent to these areas. On the other hand, the transport companies have an essential role to assist the on-site sorting of C&DW from large generators, by means of inspection of the materials stored in the skip bins (MARQUES NETO, 2009; CÓRDOBA, 2010).

Moreover, most of the municipalities elaborate their Municipal Management Plans for C&DW based on literature data, therefore, some of the reported studies seek to fill this gap, providing details on the municipal C&DW management, taking into account the peculiarities of the region of interest (MARQUES NETO, 2009; SILVA, 2010; BRÖNSTRUP, 2010; BUSELLI, 2012; LUCIO, 2013; FARIAS, 2014; MANN, 2015; ALBERICI, 2017; VARGAS, 2018).

2.5 WATERSHED AS A PLANNING UNIT

The watershed is the region comprised of a territory and several watercourses (BRASIL, 2011b). It consists of a main river and its tributaries, which carry water and sediments along its channels (GUERRA, 2003). This ecosystem is related to several natural components (land relief, soil, subsoil, flora, fauna) and can therefore be considered the most appropriate planning unit for the management of natural resources (ROSS, DEL PRETTE, 1998; MARQUES NETO, 2009).

According to the Brazilian Ministry of Cities (2004, p. 103): *"the watershed is the appropriate spatial scale to assess the impacts of current urban occupation and new urbanization projects on hydrological processes and on diffuse pollution loads"*. In this context, the watershed is a portion of space formed by a set of physical, biological, social and political elements that interact with each other, modifying the entire system. In relation to anthropic influences, the inadequate disposal of solid wastes, domestic and industrial effluents compose one of the variables that have the greatest impact on the hydrological balance of watersheds (SCHUSSEL; NETO, 2015).

According to the National Water Resources Policy, the Brazilian water management model adopts the watershed as the territorial planning unit (BRASIL, 1997). In this sense, the model is composed of Water Resources Management Units (UGRHIs), Watershed Committees and other interest groups that offer technical support (LOPES, 2007).

The Watershed Committees assist in the financing of essential projects, such as sewage treatment plants, landfills, equipment acquisition, dam construction, river clean-up, among others, since they consider that the actions related to the treatment of the domestic sewage and solid wastes are essential for a good management of the water resources (LOPES, 2003). In this sense, the study of the integrated system of solid waste management of municipalities belonging to a watershed allows a broad view of the problematic of this topic and its environmental impacts.

2.6 REMARKS OF THE CHAPTER

This chapter presented the paramount importance of the construction industry for the economic development of a country and highlighted its consequences for the environment, such as the consumption of natural resources, emissions to air, water and soil, as well as, high generation of solid waste. The last environmental aspect is the main topic of this study, therefore, an overview about the C&DW was developed in this chapter.

The first sections detailed the main characteristics of the C&DW according to the Brazilian context, including its classification (Classes A, B, C and D), generation estimative, differences in the composition among the Brazilian regions, and the infrastructures used for the C&DW management. The Brazilian laws on C&DW and the current management system adopted by the majority of the Brazilian municipalities were also presented.

The section 2.5 presented a literature review, carried out from 2015 to 2018, about C&DW management studies. In relation to the international context, it was presented mainly data on the Europe Union, United States and China, based on 17 articles. The Brazilian context was developed based on 12 articles, 6 theses and 35 dissertations. Finally, the last section comprises an explanation about the adoption of a watershed as planning unit for studies about solid waste management.

CHAPTER

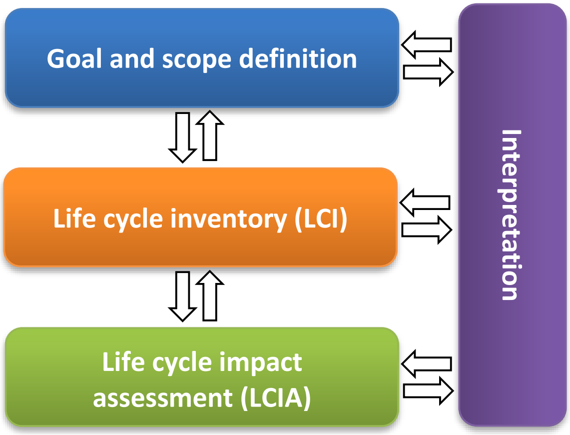
3

LIFE CYCLE ASSESSMENT

The first specific standard on the evaluation of the life cycle of a product emerged in 1997 (ISO 14.040), in the following years, three other standards with details of the methodology were published (ISO 14.041, 14.042 and 14.043). In 2006, these standards were compiled in two: ISO 14.040, with the principles and structures of the Life Cycle Assessment (LCA), and ISO 14.044 with the requirements and guidelines for LCA studies. In 2009, the Brazilian Association of Technical Standards (ABNT) published the Portuguese version of these standards.

The LCA study aims to evaluate the environmental interventions and potential impacts throughout the life cycle of a product (or service), from the raw material acquisition to the product manufacturing, use and end-of-life. For a LCA study, it is necessary to define its objective and scope; to draw up an inventory with inputs and outputs of the system under analysis; to evaluate the potential environmental impacts and, to perform the results interpretation. The LCA stages are iterative, and can be adapted during the elaboration of the study, as appropriate (Figure 34) (ABNT, 2009a).

Figure 34. Life cycle assessment stages.

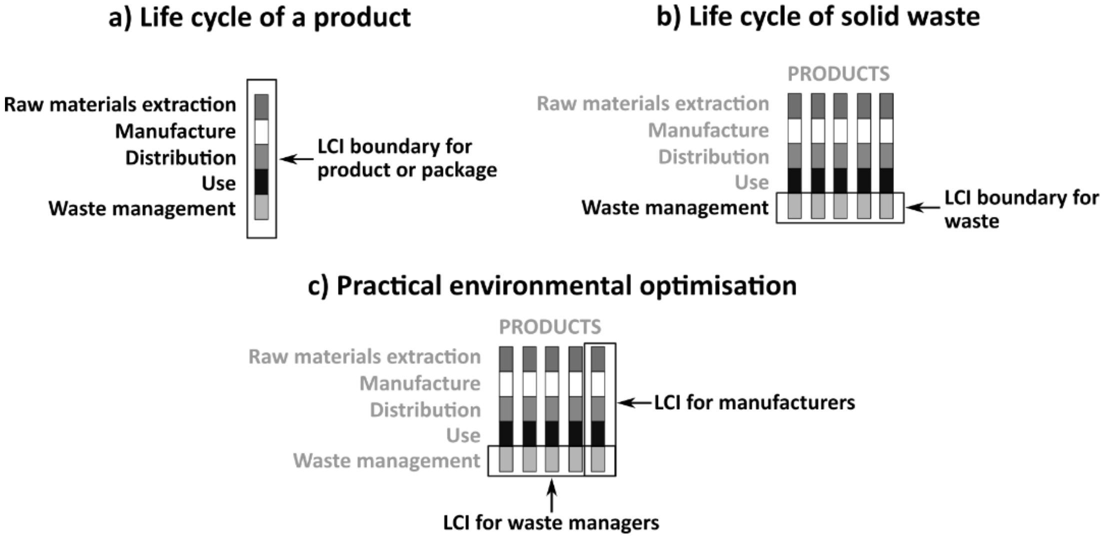


Source: adapted from ABNT (2009a).

The life cycle inventories generally collect data on the extraction of raw materials, to define the "cradle" of the product, and for the final disposal ("grave"), it is common to consider the landfill. However, when considering the life cycle of a waste, it is recommended to consider another type of "cradle", while the final disposal may also be the landfill (MCDOUGALL *et al.*, 2001).

Figure 35 shows the differences between life cycle inventories for a LCA of a product and of a solid waste management system. Manufacturers that aim to optimize the performance of their products and/or packages, develop a vertical analysis, while waste managers, municipalities and policy makers conduct a horizontal analysis to optimize the integrated waste management system. In specific, a solid waste LCI (the horizontal approach in Figure 35) attempts to assess the environmental burdens of the waste (MCDOUGALL *et al.*, 2001).

Figure 35. The life cycle of a product (a), the life cycle of waste (b), and a practical approach to environmental optimisation (c).

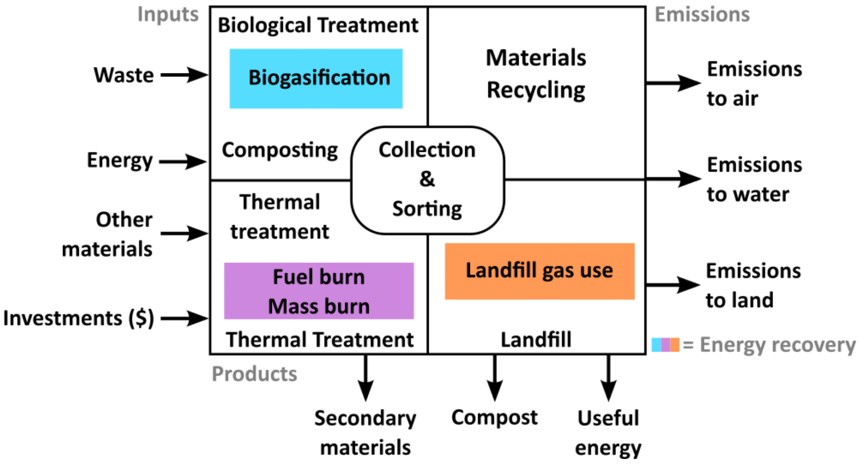


Source: adapted from Mc Dougall *et al.* (2001).

The LCA of waste management systems can be used to predict environmental and economic costs (Figure 36). The predictions may not be accurate, but provide valid estimates for planning future strategies, using data that allow investments with greater credibility (MCDOUGALL *et al.*, 2001).

Life-cycle thinking has been applied for the evaluation of waste management systems since the early 1990s (MANFREDI; TONINI; CHRISTENSEN, 2011). Currently, LCA is increasingly been used in waste management to identify strategies that prevent or minimize impacts on ecosystems, human health or natural resources. In the international context, the popularity of the LCA application on waste management systems is evidenced by several published studies, as well as by the considerable number of softwares for LCA modelling (CLEARY, 2009; LAURENT *et al*., 2014a; KHANDELWAL *et al*., 2019).

Figure 36. Solid waste management system based on the life cycle assessment methodology.



Source: adapted from Mc Dougall *et al.* (2001); Coltro (2007).

Moreover, the Waste Framework Directive of EU determines that when it is not possible to apply the waste hierarchy (prevention, preparing for re-use, recycling, other recovery methods and disposal), the Member States needs to justify by means of a life-cycle thinking the overall impacts of the waste generation and management (EUROPEAN COMMISSION, 2008).

The application of LCA is one of the guidelines of the Brazilian Solid Waste Policy (BRASIL, 2010), then, to assist this objective, the CONMETRO (National Council of Metrology, Standardization and Industrial Quality) has created the Brazilian Program of LCA (PBACV) through the Resolution nº. 03/2010, in order to gather data from Brazilian LCA studies. According to CONMETRO (2010), LCA studies are important instruments for the quantitative evaluation of the environmental effects associated to products and services, both in their manufacture and consumption, which includes the solid waste management phase. Therefore, the National Life Cycle Inventory Bank (SICV) was created in 2016, with the main purpose of share a life cycle inventories database about the current scenario of industry production and agribusiness, in order to allow the development of further studies and improvements in the available studies (IBICT, 2016).

3.1 LIFE CYCLE ASSESSMENT STAGES

This section presents the four main stages of a LCA study, in accordance with ISO 14.040:2009 - Environmental management - Life cycle assessment - Principles and structure (ABNT, 2009a) and ISO 14.044:2009 - Environmental management - Life cycle assessment - Requirements and guidelines (ABNT, 2009b), along with the recommendations of the ILCD System Manual - International Product and Process Life Cycle Data Reference System (EC-JRC, 2010).

3.1.1 STAGE 1 – GOAL AND SCOPE DEFINITION

The goal and scope definition has strong implications in the LCA study development, mainly due to the selection of the LCI modelling approach (attributional or consequential); determination of what can be concluded from the results and definition of the limitations, which assist the interpretation stage (LAURENT *et al.* 2014b).

An attributional LCA aims at describing environmentally significant physical flows to and from a life cycle and its subsystems (EKVALL; ANDRAE, 2006). This methodology makes use of historical, fact-based, measureable data of known uncertainty, and includes all the processes that significantly contribute to the system under study (EC-JRC, 2010). On the other hand, a consequential LCA investigates both direct burdens and indirect consequences of the system under study by considering various possible future scenarios: it can be defined as "change-oriented" by its aim to describe how environmentally significant flows will change in response to possible decisions (FINNVEDEN *et al.*, 2009; WEIDEMA, 2003).

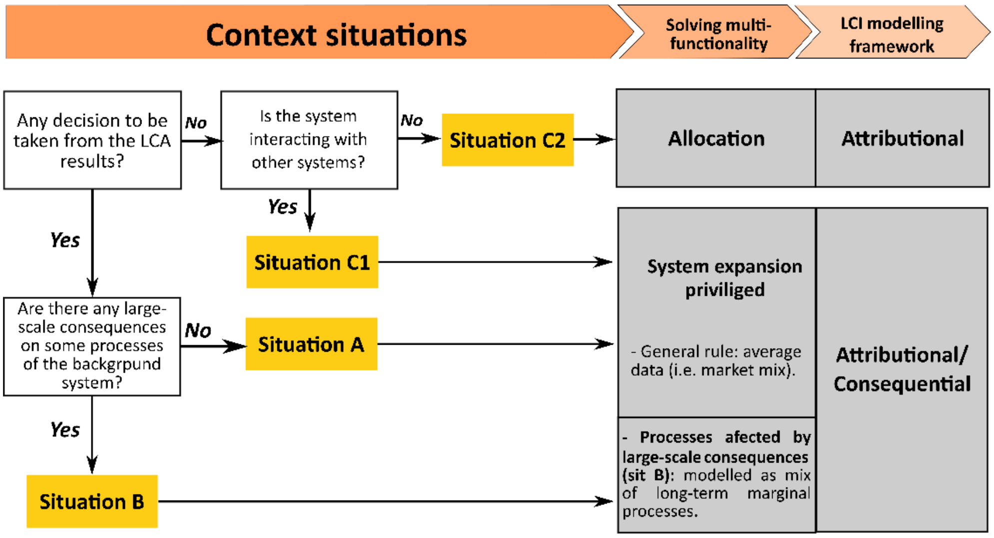
ISO 14.044 establishes that the goal should contain: the intended application; the reasons for carrying out the study; the target audience, and whether there is an intention to use the results in comparative statements to be made publicly available (ABNT, 2009a). In addition, the ILCD System Manual adds the necessity of clarifying the specific limitations of the results usability (due to applied methodology, assumptions or limited impact coverage) and, identifying who commissioned the study and name all funding or other organizations that have any relevant influence on the study, this mainly includes the experts who carry out the LCA study and their respective organizations (EC-JRC, 2010).

A system under evaluation can be divided into two main components, the foreground system, related to the processes whose selection is affected directly by decisions based on the study, and the background system, related to all other processes which interact with the foreground (CLIFT; DOIG; FINNVEDEN, 2000).

There are four main types of context situations: situation A (micro-level decision support), situation B (meso/macro-level decision support) and situations C1 and C2 (accounting with no decision support) (Figure 37) (EC-JRC, 2010). In accordance with Laurent *et al.* (2014b):

> “They are dependent on the intended decision implications of the study as well as on either the existence of large-scale consequences on some processes in the background system and in other systems (differentiation of situations A and B), or the existence/consideration of interactions of the system with other systems (differentiation of situations C1 and C2, the latter being very rare)” (LAURENT *et al*., 2014, p. 592).

Figure 37. Identification of context situations and LCI modelling framework.



Source: Laurent *et al.* (2014b).

An adequate identification of the study's context situation is important as it determines the type of the LCI modelling, which influence the results and interpretation. For example, the use of allocation or expansion system in an attributional LCA study may generate opposite results (LAURENT *et al*., 2014b). The allocation consists of the partition of the inputs or outputs of a process or product system between the product system under study and other product system(s), while the system expansion comprises the addition of specific processes or products and their life cycle inventories to the analysed system (EC-JRC, 2010).

The ILCD manuals were developed focused on products and services, not providing a specific content on how to apply these concepts in waste management studies, therefore, most of the published LCA studies on waste management did not clearly determine the context target of the study. In accordance with Laurent *et al.* (2014b), several studies seem to adopt the evaluation at the micro level (situation A), in which specific scenarios of waste treatment are investigated in a specific region or company.

The scope must be sufficiently defined to ensure that the coverage and level of detail of the study are consistent and sufficient to meet the established goal (ABNT, 2009a), including the following items:

- **Product system:** set of elementary processes, materially and energetically connected, necessary for one or more functions defined in the goal and scope (SILVA; BRÄSCHER, 2011).
- **Functional unit (FU):** the function of the product or service studied in quantitative terms. It is the reference flow to which all other flows (inputs and outputs) of the system are related (EC-JRC, 2010).
- **System boundaries:** a set of criteria that specify which elementary processes comprise the product system (ABNT, 2009a).
- **Allocation procedure:** definition of the proportionality criterion to be used for the distribution of inputs and outputs (SILVA; BRÄSCHER, 2011).
- **Impact categories and life cycle impact assessment methodology:** the impact categories represent the relevant environmental issues to which the results of the life cycle inventory analysis can be associated (such as, global warming, acidification, human toxicity, etc.) (ABNT, 2009b). The LCIA methodologies can be grouped into two types:
  - *Midpoint:* the characterisation uses indicators located along the environmental mechanism, before reaching the endpoint of the category (MENDES, 2013).
  - *Endpoint:* the characterisation considers the whole environmental mechanism to its endpoint, i.e. refers to specific damage related to the wider area of protection (human health, natural environment or natural resources) (MENDES, 2013).
- **Data requirements:** the type of data required to meet the goal and scope of the study. It includes the definition of time, geographic and technological coverage, accuracy, completeness, representativeness, consistency, reproducibility and uncertainty (SILVA; BRÄSCHER, 2011).
- **Critical analysis:** process to ensure the consistency between the study and the principles and requirements of LCA standards (ABNT, 2009b).
- **Type and format of the study report:** document that reports the LCA results to the target audience (SILVA; BRÄSCHER, 2011).

3.1.2 STAGE 2 - LIFE CYCLE INVENTORY (LCI)

The life cycle inventory comprises the quantification of the inputs and outputs for each process included in the system boundary (ABNT, 2009a). This stage is considered iterative because, during data gathering, the knowledge of the system under study increases, therefore, the goal and scope should be updated when necessary (RIBEIRO, 2003). According to ISO 14.044 (ANBT, 200b) this stage has the following phases:

- **Data gathering:** a process that most often demands many resources, especially time, so the limitations should be considered in scope and be documented in the study report. In general, the data for each elementary process included in the system boundary can be classified into: (a) energy raw material, auxiliary and other physical inputs; (b) products, co-products and waste; (c) emissions to air, water and soil, and (d) other environmental burdens.
- **Calculation procedures:** include the validation of the data gathered, the correlation of the data to the elementary processes, and the correlation of the data to the reference flows and the functional unit.

A set of software has been developed to assist the LCA studies, due to the significant amount of data to be calculated and analysed. In the area of waste management, one of the most used is SimaPro, followed by EASEWASTE and Gabi. For the LCI elaboration, it is common to use secondary data, which are obtained from databases such as Ecoinvent and BUWAL (BOVEA; POWELL, 2016; LAURENT *et al.*, 2014b). However, it is recommended to use primary data whenever possible; especially when it is related to processes that occur in the foreground system, such data can be reported by third parties (such as companies, government agencies, environmental agencies, laboratories, etc.) or obtained by field measurements.

3.1.3 STAGE 3 - LIFE CYCLE IMPACT ASSESSMENT (LCIA)

The life cycle impact assessment stage aims to study the significance of the potential environmental impacts, based on the LCI results. In general, this process associates inventory data with specific impact categories and indicators, with the purpose of understanding these impacts and providing information for the interpretation stage. The mandatory elements are: (i) selection of impact categories, category indicators and characterisation models; (ii) correlation of LCI results (classification) and, (iii) calculation of results of category indicators (characterisation) (ABNT, 2009b).

Currently, there are no accepted methodologies for consistently and accurately associating inventory data with potential specific environmental impacts. As a result, a number of impact assessment methods have been developed, which can be grouped into two types:

- *Midpoint methodologies*: the characterisation uses indicators located throughout the environmental mechanism before reaching the endpoint of the category (ABNT, 2009a). *LCIA midpoint methods*: CML, EDIP, Impact 2002+, TRACI, LUCAS, ReCiPe, USEtox, Impact 2002+ World;
- *Endpoint methodologies*: the characterisation considers the whole environmental mechanism to its endpoint, i.e. refers to specific damage related to the broader area of protection, such as human health, natural environment or resources (ABNT, 2009a). *LCIA endpoint methods*: EPS2000, Eco-Indicator 99, LIME, Impact 2002+, ReCiPe.

Moreover, there are LCIA methodologies comprising midpoint and endpoint approaches, such as Impact 2002+ and ReCiPe.

In 2011, the ILCD published the recommendations for LCIA in the European context, based on existing environmental impact assessment models and factors, which are listed in Table 7. The recommended characterisation models and associated characterisation factors are classified according to their quality into three levels: “I” (recommended and satisfactory), level “II” (recommended, but in need of some improvements) or level “III” (recommended, but to be applied with caution). The classification “interim” indicates that a method was considered the best among the analysed methods for the impact category, but still immature to be recommended (EC-JRC, 2011).

There are three optional elements in the LCIA: normalisation, grouping and weighting. The most used is normalisation, in which the results of the category indicators are related to a reference situation, providing information about their relative significance (ABNT, 2009b). After the normalisation, it is possible to compare the results among all impact category, as they acquire a single unit, so it is possible to verify the presence of errors and inconsistencies (for example, the lack of inventory data can generate low normalized values, close to zero) (EC-JRC, 2010).

However, these methods have been developed in countries such as the Netherlands, Denmark, Switzerland, Sweden, the United States, among others, which have environmental, socioeconomic and cultural realities considerably different from Brazil. These countries use national data, values from their respective regions or global values as a reference. Thus, the use of these local and regional references in studies conducted in any other country, can lead to questionable reliability results (SOUSA, 2008).

Table 7. Recommended methods and their classification at midpoint for the European context, according to International Reference Life Cycle Data System.

Impact category	Recommended default LCIA method	Indicator	Classification*
Climate change	Baseline model of 100 years of the IPCC	Radiative forcing as Global Warming Potential (GWP100)	I
Ozone depletion	Steady-state ODPs 1999 as in WMO assessment	Ozone Depletion Potential (ODP)	I
Human toxicity, cancer effects	USEtox model	Comparative Toxic Unit for humans (CTUh)	II/III
Human toxicity, non-cancer effects	USEtox model	Comparative Toxic Unit for humans (CTUh)	II/III
Particulate matter/Respiratory inorganics	RiskPoll model and Greco *et al*. 2007	Intake fraction for fine particles (kg $PM_{2.5}$-eq/kg)	I
Ionising radiation, human health	Human health effect model as developed by Dreicer *et al*. 1995 (Frischknecht *et al*., 2000)	Human exposure efficiency relative to U235	II
Ionising radiation, ecosystems	No methods recommended		Interim
Photochemical ozone formation	LOTOS-EUROS as applied in ReCiPe	Tropospheric ozone concentration increase	II
Acidification	Accumulated Exceedance	Accumulated Exceedance	II
Eutrophication, terrestrial	Accumulated Exceedance	Accumulated Exceedance	II
Eutrophication, aquatic	EUTREND model as implemented in ReCiPe	Fraction of nutrients reaching freshwater end compartment (P) or marine end compartment (N)	II
Ecotoxicity (freshwater)	USEtox model	Comparative Toxic Unit for ecosystems (CTUe)	II/III
Ecotoxicity (terrestrial and marine)	No methods recommended		
Land use	Model based on Soil Organic Matter	Soil Organic Matter	III
Resource depletion, water	Model for water consumption as in Swiss Ecoscarcity	Water use related to local scarcity of water	III
Resource depletion, mineral, fossil and renewable**	CML 2002	Scarcity	II

Notes: *A mixed classification sometimes is related to the application to different types of substances. **Depletion of renewable resources is included in the analysis but none of the analysed methods is mature for recommendation. Classification: level “I” - recommended and satisfactory; level “II” - recommended, but in need of some improvements; and level “III” - recommended, but to be applied with caution. Source: EC-JRC (2011).

3.1.4 STAGE 4 - INTERPRETATION

The interpretation includes the identification of significant issues based on the results of the previous stages along with the evaluation in comparison to the goal and scope, in order to provide the conclusions, limitations and recommendations of the study. This stage is also iterative, then, in some cases it is necessary to improve the quality of LCI data or update the scope, for example. In addition, this stage includes the analyses of completeness, sensitivity and consistency (ABNT, 2009b).

The completeness analysis aims to ensure that all significant data required for interpretation are available and complete, while the consistency analysis determines whether the assumptions, methods and data are consistent with the defined goal and scope. Finally, the sensitivity analysis evaluates the reliability of the final results and conclusions, determining how they are affected by data uncertainties, methods of allocation or other calculation procedures (ABNT, 2009b).

In LCA studies about C&DW management, aspects related to the evaluation of elements for enhancing the reliability of the results are rarely included. Usually, the studies apply only the sensitivity analysis, based on the variation of the parameters related to transport distance, energy consumption, type of transport, secondary data source, application of different LCIA methods, recycling rates, waste composition, among others (BOVEA; POWELL, 2016).

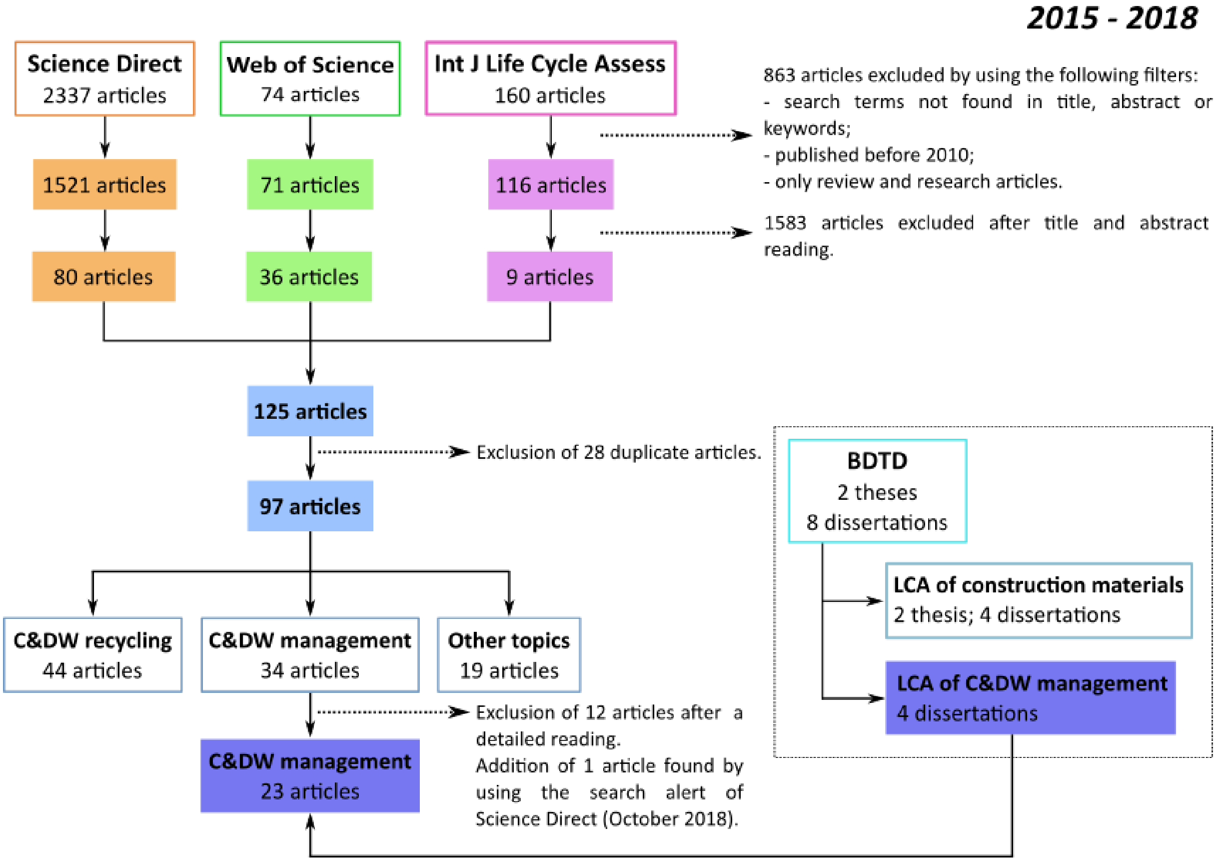
3.2 LIFE CYCLE ASSESSMENT STUDIES ON C&DW MANAGEMENT

The literature review about the LCA studies on C&DW management was elaborated based on the PRISMA statements (MOHER *et al.*, 2009). The search was performed in Science Direct and Web of Science databases and, in The International Journal of Life Cycle Assessment, since it is not included in the selected databases. The Brazilian Digital Library of Theses and Dissertations (BDTD) was used to search the PhD theses and Master dissertations. The search was carried out from 2015 until 25th May 2018, by using the following search strategy: *(“construction and demolition waste” OR “construction waste” OR “demolition waste” OR “C&DW” OR “C&D” OR “CDW”) AND (“life cycle assessment” OR “LCA”) AND (“management”)*.

The first search resulted in 2571 articles, after the exclusion of those without the search topics in the title, abstract or keywords and published before 2010, 1708 articles were obtained (Figure 38). After the title and abstract reading and exclusion of duplicate articles, 97 articles were obtained. These articles were classified in LCA studies on C&DW management

(34 articles), LCA studies on C&DW recycling (44 articles) and LCA studies about other topics related to C&DW, such as LCA of building or construction materials (19 articles). After a detailed reading of the 34 studies on C&DW management, 12 articles were excluded, mainly due to the absence of details on the LCA methodology. Moreover, one study was added by using the search alert of the Science Direct database, resulting in the selection of 23 studies for this literature review. Finally, the search on BDTD resulted in 2 theses and 8 dissertations, most of them related to LCA of construction materials (2 theses and 4 dissertations), followed by LCA on C&DW management (4 dissertations).

Figure 38. Data about the search on LCA studies focused on C&DW management carried out from 2015 to 2018.



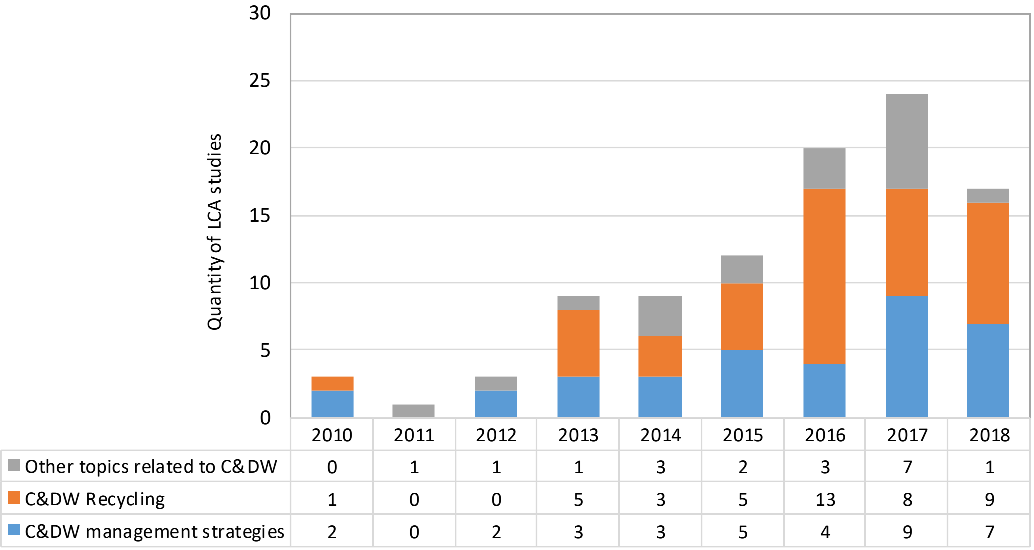
Source: Author (2019).

In the context of solid waste management, C&DW is one of the challenges for public managers, mainly due to its high volume and heterogeneous composition. As this type of waste usually presents low pollutant content, in some cases, its management is neglected. In this sense, the LCA studies allow the evaluation of scenarios that indicate the management option with the lowest environmental impacts. Usually, the scenarios comprise reuse, recycling and landfilling. The majority of LCA studies applied to C&DW has been developed in Europe

(66.3%), followed by America (17.5%), with emphasis on the United States; Asia (10.0%), with emphasis on China; Oceania (3.8%) and Africa (2.5%) (BOVEA; POWELL, 2016).

These studies increased in 2003 and 2010, coiciding with the publication of the European Directive 2002/91/EC (on the energy performance of buildings), replaced by Directive 2010/31/EC (BOVEA; POWELL, 2016). In the last years (2013-2018) the number of studies has increased (Figure 39). On the other hand, in comparison with the number of studies on municipal solid waste management, LCA studies on C&DW management are still a minority (LAURENT *et al*., 2014a).

Figure 39. Classification of the 98 analysed articles according to the year and aim of the LCA study.



	2010	2011	2012	2013	2014	2015	2016	2017	2018
■ Other topics related to C&DW	0	1	1	1	3	2	3	7	1
🟧 C&DW Recycling	1	0	0	5	3	5	13	8	9
🟦 C&DW management strategies	2	0	2	3	3	5	4	9	7

Source: Author (2019).

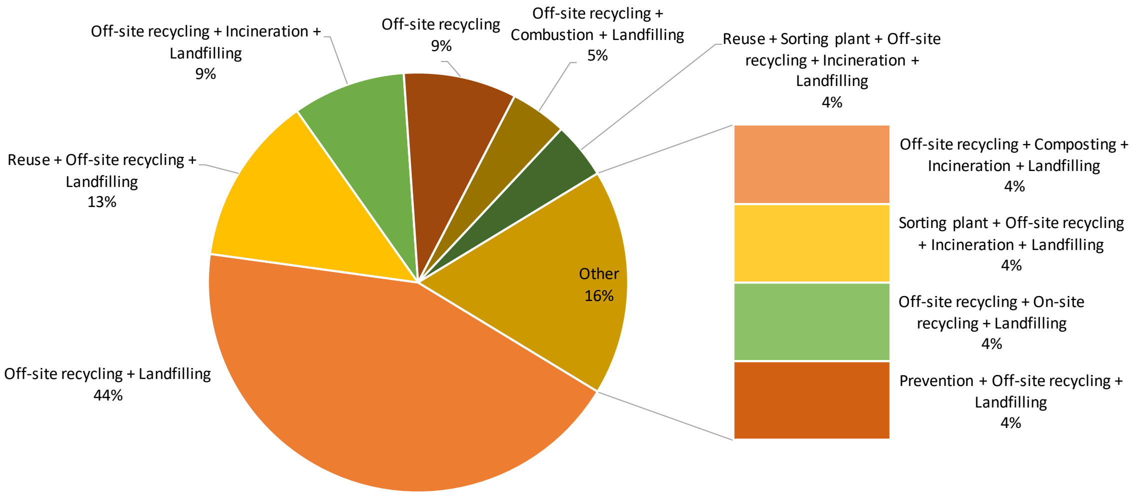
The analyses of 80 articles published about LCA and C&DW management carried out by Bovea and Powell (2016) revealed that off-site recycling and incineration, both combined with landfilling, are the main management strategies, reuse and on-site recycling are less used. The authors also included the following notes about the LCA methodology applied to C&DW management:

- ***System boundaries:*** in all revised articles, the system boundary considers the C&DW after its generation as the "cradle" (the construction/demolition process remains outside the system boundary); the remaining of the system boundary is specific to each study. For example, when recycling is considered as a strategy for some C&DW fractions, the system boundary can be expanded to consider avoided burdens (credits) due to the production of a secondary material as a substitute for a primary material (virgin). The avoided burdens related to on-site or off-site recycling or incineration are included in almost 75% of the analysed studies.

- ***Transport:*** there is a general agreement to include the transport between the construction site and treatment facilities within the system boundary. However, the impact due to the use of containers for waste storing (skip bins and other types of containers) is rarely considered; being covered only by Mercante *et al*. (2012).
- ***Data source:*** most of the studies use secondary data in the LCI elaboration, based on literature sources or databases. Case studies from Europe usually use inventory data from Ecoinvent, BUWAL250 or Idemat; United States studies use the USLCI or Ecoinvent; and Australian studies use the Australian National Life Cycle Inventory; only ten of the reviewed studies include data obtained from primary sources.
- ***Impact categories:*** “global warming” and “energy” are the main impact categories included in the analysed studies, followed by "acidification", "eutrophication" and "ozone layer depletion". The characterisation factors from the CML methodology are mainly used to obtain indicators for these categories.

The general data about the 23 selected LCA studies on C&DW management are listed in Table A2.1 (Appendix A2). Table A2.2 (Appendix A2) presents the location, aim of the study and waste management strategies of each study. This preliminary analysis reveals that most studies were developed in Europe (13 studies; 57%), followed by America (5 studies; 22%), Asia (4 studies; 17%) and Oceania (1 study; 4%). In addition, Figure 40 shows that the off-site recycling combined with landfilling is the main waste management strategy (10 studies; 44%), followed by off-site recycling combined with landfilling and reuse (3 studies; 13%) and, off-site recycling combined with landfilling and incineration (2 studies; 9%). The remaining studies adopted only off-site recycling as alternative (2 studies; 9%) or combined different management strategies (6 studies; 25%) in accordance with the goal and scope definition.

Figure 40. Management strategies of the 23 analysed LCA studies on C&DW management.



Source: Author (2019).

The high C&DW generation rates in Europe has overburden the landfills capacity, and as a consequence, most of the studies conducted in this region aim to evaluate the environmental impacts of the C&DW from construction, use, refurbishment and/or demolition stages of buildings, in order to determine the environmental viability of other management alternatives, such as reuse and recycling (ORTIZ; PASQUALINO; CASTELLS, 2010; COELHO; BRITO, 2012; MARTÍNEZ; NUÑEZ; SOBABERAS, 2013; ZAMBRAMA-VASQUEZ *et al.*, 2016; VITALE *et al.*, 2017).

Demolition wastes represent a significant portion of the total C&DW generated, then, some studies have analysed the influence of selective demolition to improve the environmental performance of waste management compared to conventional demolition (MARTÍNEZ; NUÑEZ; SOBABERAS, 2013; VITALE *et al.*, 2017; DI MARIA; EYCKMANS; ACKER, 2018). In addition, there is an increase of studies focused on the characterisation of building material stocks at the urban scale, in order to assess the potential environmental impact associated with the end-of-life of buildings to support decision on waste management strategies (MASTRUCCI *et al.*, 2017).

Moreover, other studies evaluate the environmental performance of C&DW management systems of a specific region, mainly considering the recycling and transport stages (BLENGINI; GARBARINO, 2010; MERCANTE *et al.*, 2012; BORGHI; PANTINI; RIGAMONTI, 2018). The remaining studies, besides evaluating the environmental impacts of C&DW management systems, have focused on specific topics, such as the leaching of inorganic pollutants from C&DW landfilling and utilisation of recycled aggregates in road construction (BUTERA; CHRISTENSEN; ASTRUP, 2015); LCA combined with life cycle cost (DI

MARIA; EYCKMANS; ACKER, 2018); analysis of specific wastes, as those from deconstruction and milling of old pavements (PANTINI; BORGHI; RIGAMONTI, 2018) and, the inclusion of waste prevention activities in the evaluation of construction waste management scenarios (BIZCOCHO; LLATAS, 2018).

Studies in America are concentrated in the United States, which aim to evaluate the environmental impacts of management alternatives for the C&DW from end-of-life of buildings generated in a particular region (CARPENTER *et al*., 2013; KUCUKVAR; EGILMEZ; TATARI, 2014; YAZDANBAKHSH, 2018). The studies have proposed different approaches in addition to the LCA methodology, such as an economic input–output-based hybrid LCA (KUCUKVAR; EGILMEZ; TATARI, 2014) and, a framework for modelling alternative waste management scenarios to measure and compare the impacts at two scales of strategy and decision-making (YAZDANBAKHSH, 2018). A Brazilian study compared the current and six management scenarios, taking into account the C&DW from small generators of a medium-size municipality (PENTEADO; ROSADO, 2016) and, a Canadian study proposed a conceptual C&DW management framework to maximise the 3R (reduce, reuse and recycle) and minimise the C&DW landfilling (YEHEYIS *et al*., 2013).

The studies developed in Asia are from Hong Kong and Shenzhen city, China, compare management strategies for construction waste (HOUSSAIN; WU; POON, 2017) and demolition waste (WANG *et al*., 2018a) respectively. Another study focused on the environmental profile of the wood waste management (HOSSAIN; POON, 2018). Some of them have applied the LCA methodology combined with other tool, such as the Building Information Modelling (BIM), to quantify the carbon emissions generated over the life cycle of building demolition waste (WANG *et al*., 2018b), and the willingness-to-pay approach, to determine the environmental costs and benefits of recycling, compared with a traditional landfill (WANG *et al*., 2018a). Oceania is represented by one study from New Zealand, which aims to verify if the material procurement and construction waste management strategies could reduce the environmental impacts and provide benefits to buildings in terms of energy efficiency (GHOSE; PIZZOL; MCLAREN, 2017).

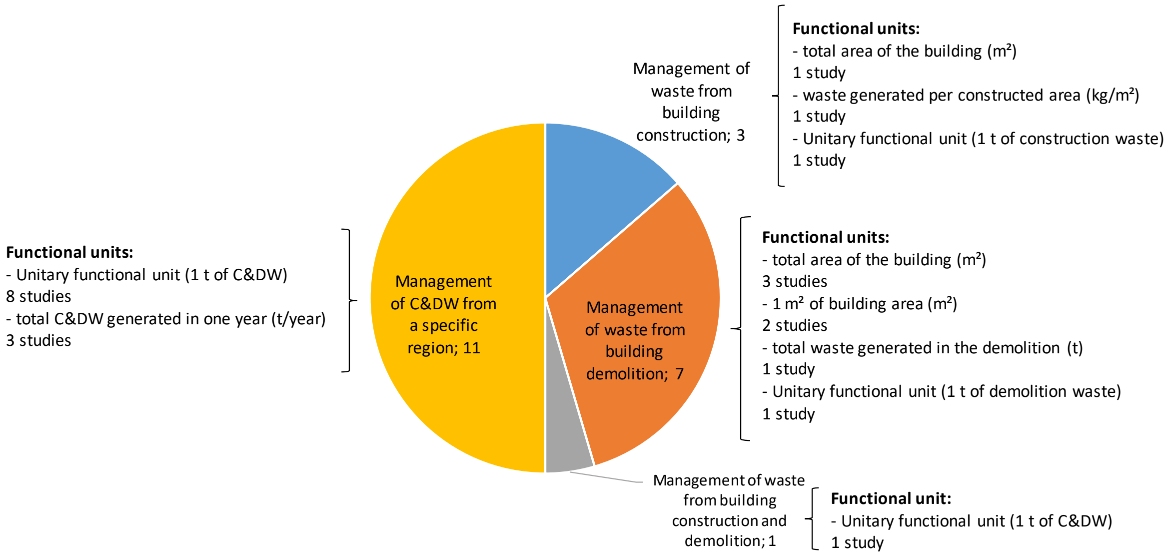
Table A2.3 (Appendix A2) presents some methodological aspects used by the selected LCA studies on C&DW management, including functional unit, C&DW composition, system boundaries and life cycle inventory data, which are discussed below.

The LCA study is developed based on the functional unit, which provides a reference for all inputs and outputs in the inventory, ensuring the comparability of results

(ABNT, 2009a). In accordance with Laurent *et al*. (2014b), the LCA studies on solid waste management systems have been used four major types of functional unit: (i) unitary functional unit (e.g. management of 1 tonne of waste); (ii) waste generated in a region in a specific period of time; (iii) quantity of waste entering a particular facility and, (iv) the waste by-products (e.g. amounts of recovered energy or recycled material). Among these types, the unitary functional unit is the most used. However, the authors highlighted that LCA studies on solid waste management systems require additional information on the waste composition, characteristics of the region under study and, any other significant aspects to ensure the comparability of the systems.

Figure 41 presents the functional units utilised by the analysed studies in this literature review. Most of the LCA studies on C&DW management system of a specific region utilised the unitary functional unit (BLENGINI; GARBARINO, 2010; MERCANTE *et al*., 2012; KUCUKVAR; EGILMEZ; TARTARI, 2014; BUTERA; CHRISTENSEN; ASTRUP, 2015; PENTEADO; ROSADO, 2016; BORGHI; PANTINI; RIGAMONTI, 2018; HOUSSAIN; POON, 2018; PANTINI; BORGHI; RIGAMONTI, 2018), the remaining studies adopted the total C&DW generated in a year (CARPENTER *et al*., 2013; YAZDANBAKHSH, 2018) and the supply of an equal amount of fine aggregates for road construction and coarse aggregates for concrete production (DI MARIA; EYCKMANS; ACKER, 2018).

Figure 41. Types of functional units used by the selected LCA studies on C&DW management.



Source: Author (2019).

The LCA studies on management system of wastes from building construction and/or demolition utilised as functional unit the total or unitary area of the building (COELHO; BRITO, 2012; MARTÍNEZ; NUÑEZ; SOBABERAS, 2013; GHOSE; PIZZOL; MCLAREN, 2017; MASTRUCCI *et al*., 2017; VITALE *et al*., 2017), the total or unitary amount of waste generated (ZAMBRAMA-VASQUEZ *et al*., 2016; HOUSSAIN; WU; POON, 2017; WANG *et al*., 2018a; WANG *et al*., 2018b; BIZCOCHO; LLATAS, 2018) or, the amount of construction waste generated per m² of built area (ORTIZ; PASQUALINO; CASTELLS, 2010).

Among the LCA studies on C&DW management systems of a specific region that utilised the unitary functional unit, most presented a detailed composition of the waste along with the peculiarities of the region under study (ORTIZ; PASQUALINO; CASTELLS, 2010; MERCANTE *et al*., 2012; BUTERA; CHRISTENSEN; ASTRUP, 2015; PENTEADO; ROSADO, 2016; BORGHI; PANTINI; RIGAMONTI, 2018) and, two studies refer only a specific type of C&DW, as wood (HOUSSAIN; POON, 2018) and asphalt (PANTINI; BORGHI; RIGAMONTI, 2018). On the other hand, two studies did not specify clearly the functional unit utilised (KUCUKVAR; EGILMEZ; TARTARI, 2014; YAZDANBAKHSH, 2018).

The waste composition is a fundamental data to develop a solid waste management plan, since this information allow to determine the feasibility of prevention, reduction, reuse and recycling alternatives (CASTRO, 1997). In this sense, the type of materials present in the waste flow may affect the results of LCA studies on waste management systems (BISINELLA *et al*., 2017). C&DW composition data of the analysed studies were obtained from reports of environmental public departments, literature, previous studies developed by the authors themselves or by a characterisation procedure performed specifically for the study. From now on, the discussion is focused on the LCA studies about C&DW management systems from a specific region[4], since their objectives are closer to those of the present study.

Table 8 presents the C&DW composition in percentage by mass provided by six studies; the five other studies included a qualitative composition (BUTERA; CHRISTENSEN; ASTRUP, 2015; YAZDANBAKHSH, 2018), or presented the data in a graph, not allowing the reading of the exact percentage values of each composition fraction (KUCUKVAR; EGILMEZ; TARTARI, 2014), and two studies are related to only one type of waste, like wood (HOSSAIN; POON, 2018) or asphalt (PANTINI; BORGHI; RIGAMONTI, 2018).

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[4] Studies number 2, 4, 5, 8, 9, 10, 16, 18, 19, 21 and 23 (as referenced in Tables 10 and 11).

Table 8. C&DW composition data of the LCA studies on C&DW management system of a specific region.

Authors (year)		Blengini and Garbarino (2010)	Mercante *et al*. (2012)[1,2]		Carpenter *et al*. (2013)[1]	Penteado and Rosado (2016)[1]	Borghi, Pantini and Rigamonti (2018)	Di Maria, Eyckmans and Acker (2018)[1]
Location		Italy	Spain		United States	Brazil	Italy	Belgium
Code	**Composition**	**% (by mass)**						
1701	Concrete, bricks, tiles and ceramics	-	-	-	-	-	10.9	-
170101	Concrete	2.30	-	-	-	8	-	-
170103	Tiles and ceramics	-	-	-	-	12	-	-
170107	Mixtures of concrete, bricks, tiles and ceramics	5.10	82.00	83.22	15	-	-	88
170201	Wood	-	1.50	0.62	40	5	-	1
170203	Plastic	-	0.50	0.003	3	-	-	0.5
170302	Bituminous mixtures	15.70	-	-	-	-	8.4	-
170407	Mixed metals	-	0.70	0.04	6	-	-	4
170504	Soil and stones	28.60	-	-	-	50	-	-
170604	Insulation materials	-	-	-	-	-	-	-
170802	Gypsum-based construction materials	-	-	-	14	-	0.3	-
170904	Mixed C&DW	47.30	-	-	-	10	80.4	-
-	Paper/cardboard	-	0.30	0.02	2	-	-	-
-	Roofing (asphalt shingles)	-	-	-	10	-	-	-
-	Other waste	1.1	-	-	10	-	-	0.5
-	Hazardous waste	-	-	-	-	-	-	6
-	Reject with hazardous	-	15.00	16.09	-	-	-	-
-	Refuses	-	-	-	-	15	-	-

Notes: [1]C&DW characterisation data adapted to the European List of Waste codes. [2]Input C&DW of a sorting and treatment plant type I (left) and type II (right).

The mineral C&DW represents the main fraction of all C&DW compositions of the analysed studies, with exception of the studies conducted in the United States (CARPENTER *et al*., 2013; KUCUKVAR; EGILMEZ; TARTARI, 2014), in which the wood is the main fraction corresponding to the construction technique used in that region. Kucukvar, Egilmez and Tartari (2014) presented the waste composition related to different US building sectors: drywall and wood wastes are the main fractions generated in residential renovation or new construction, while wood and concrete wastes are the main generated in residential demolition, commercial renovation and commercial new construction; and wood and ferrous metals are the main generated in the commercial demolition. Another study from the US (YAZDANBAKHSH, 2018) adopted only the analysis of the mineral fraction, which is composed by concrete, brick and clay tiles, unwanted rocks and inorganic soils.

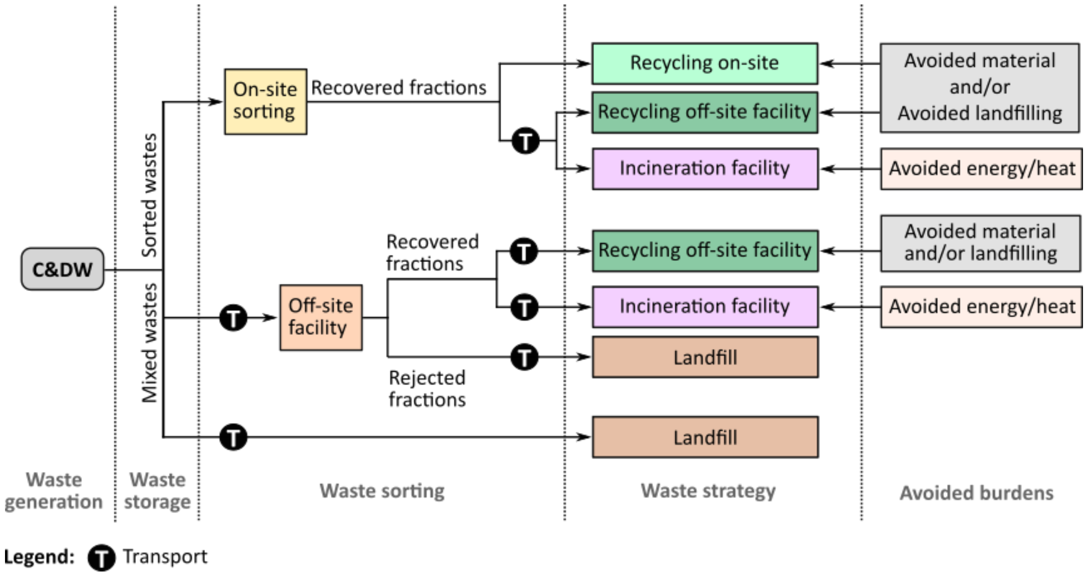
Butera, Christensen and Astrup (2015) also analysed solely the management of the mineral fraction, including concrete, possibly mixed with soil, tiles, bricks and mortar. The authors excluded the other material fractions potentially present in C&DW (plastic, paper, gypsum, wood and metal), as a consequence of the sorting at source performed during the demolition process in accordance to Danish legislation. Penteado and Rosado (2016) followed this same approach, as well as Borghi, Pantini and Rigamonti (2018), who analysed the management of the non-hazardous C&DW. Mixtures of bituminous material were only present in the C&DW composition of Italian studies, while hazardous wastes were only reported in the studies from Spain and Belgium. Finally, it is important to highlight the large amount of refuse in the Brazilian study, which refers to household solid waste mixed with the C&DW.

The system boundary determines the unitary processes considered in the LCA study. Figure 42 shows a generic system boundary with the main alternatives considered by the LCA studies on C&DW management. In addition, this step also includes information on the geographical, temporal and technological coverage of the study.

The analysed studies present the system boundary by using a figure and/or a description of each unitary process, however, those studies that chose to use LCA along with other methodologies (KUCUKVAR; EGILMEZ; TARTARI, 2014; YAZDANBAKHSH, 2018) do not have a clear definition of the system boundary.

In most studies, the system boundary has as first stage the collection of the C&DW from the construction and/or demolition and, the transport to off-site sorting and recycling and/or to an appropriate landfill. Usually, the mineral fraction sorting is performed along with the recycling process, or in some cases, a mobile facility is used in the worksite or in collection centres. In relation to the non-mineral fraction, there are studies that consider only the ferrous metals, while others include the management of all non-mineral fractions.

Figure 42. System boundary for LCA studies on C&DW management.



Source: adapted from Bovea and Powell (2016).

The next stage is the life cycle inventory elaboration, which is performed by data collection and calculation procedures for the quantification of the inputs and outputs of each unit process included in the system boundary. This stage can be conducted in accordance with two approaches: attributional or consequential. Among the analysed studies, only one reported the use of a consequential approach (BUTERA; CHRISTENSEN; ASTRUP, 2015). Others adopted an attributional approach, although only two (VITALE *et al*., 2017; DI MARIA; EYCKMANS; ACKER, 2018) has justified explicitaly this choice. The absence of this aspect in ISO 14.040 and ISO 14.044 may be a reason for the absence of this information in the studies.

Another important aspect that affect the LCI elaboration is the methodology used to deal with multifunctional processes. Most analysed studies avoided the allocation, by using the system expansion method (also called "avoided burden" or "substitution"), in which the life cycle inventory of the processes or products replaced by the obtained co-products is subtracted from the analysed system (FINNVEDEN *et al*., 2009; EC-JRC, 2010).

In this context, it is important to note that the secondary material obtained by the recycling may have lower quality compared to the primary material that it will replace. In this way, it is necessary to report the substitution factor adopted and justify it. Most of the studies have considered the substitution factor of 1:1 for the mineral fraction (i.e. 1 t of recycled aggregates substitutes 1 t of natural aggregates), however, some assumptions have been adopted. For instance, Blengini and Garbarino (2010) considered three types of recycled aggregates (A - high quality RA for concrete and road construction; B - medium quality RA for road, airport and harbour construction and, C - low quality RA for environmental filling and rehabilitation of depleted quarries and landfill sites), and different recycling facilities configurations (stationary - produces the three types of RA; semi-mobile - produces the RA type B and C and, mobile - produces only the RA type C). In this context, that LCA study assumed that "*RA of type A, B and C roughly correspond to the equivalent type of NA that would be employed for the same end-use*".

Borghi, Pantini and Rigamonti (2018) proposed a methodology to determine the substitution factor for RA, considering the quality and market demand, based on data from Lombardy region (Italy) in 2014. This methodology, performed by the Equation 1, is coherent with the reality of the current scenario of C&DW recycling and is an effective tool to understand in what magnitude the RA substitutes NA. However, studies can still be developed to improve the methodology for determining the RA quality coefficient (Q_1).

$$R = Q_1 \times Q_2 \times M \qquad \text{(Equation 1)}$$

Where:

- R = replacement coefficient;
- Q_1 considers the quality of RAs in terms of "clean composition".
    - $Q < 1$, when there are impurities, such as soil, woof, plastics, etc.
- Q_2 considers the technical characteristics of RAs compared to those of the substituted material in relation to the specific application.
    - $Q_2 = 1$, when RA are used in road construction (unbound materials and sub-base layers).
    - $Q_2 < 1$, when RA are used for environmental reclamations and fillings.
- M is the market coefficient and is defined as the ratio between the amount of RAs sold and produced in the recycling facility in a time period
    - $M = 0$, when all the produced RAs are unsold due to the absence of demand;
    - $M = 1$, when RA are totally sold.

Among the studies that consider the non-mineral fraction management, some included only the avoided burdens (environmental credits or benefits) from the ferrous metal recycling (BLENGINI; GARBARINO, 2010; BORGHI; PANTINI; RIGAMONTI, 2018); the avoided burdens from wood and ferrous metal recycling (DI MARIA; EYCKMANS; ACKER, 2018); the avoided burdens from different alternatives of wood management (CARPENTER *et al.*, 2013; HUSSAIN; POON, 2018) or, the avoided burdens from recycling of metal, plastic, paper/cardboard and wood (MERCANTE *et al.*, 2012). These LCA studies adopted different approaches to consider the environmental benefits from recycling, taking into account the ferrous metal as example. The following approaches were used:

- Blengini and Garbarino (2010) considered the impacts generated by steel recycling via electric arch route (secondary steel), while the avoided virgin product is primary steel (converter steel), re-melting yield from steel scrap was assumed to be 90%.
- Mercante *et al.* (2012) considered that the ferrous metal substitutes the pig iron at a substitution ratio of 1:1.
- Di Maria, Eyckmans and Acker (2018) considered that ferrous metals is re-melted in furnaces to produce new iron and steel, then, it is assumed that the recovered metals can avoided the mining iron ores, which are used as raw materials to produce an equivalent amount of iron and steel.

Gala, Raugei and Fullana-i-Palmer (2015) provided an alternative method for calculating the environmental credits associated with material recycling in LCA of waste management systems. As in the aforementioned method, there is a need for research to determine quality factors (Q), mainly for plastics. Equation 2 can be used to calculate the environmental credit associated to 1 tonne of recycled material.

$$Environmental\ credit\ = x\ \times REC + (1\ - x) \times Q\ \times VIR \qquad \text{(Equation 2)}$$

Where:

- x is the proportion of recycled material in the average market mix.
- (1-x) is the proportion of virgin material in the average market mix.
- Q is the quality factor of recycled material vs. virgin material ($Q \leq 1$).
- REC is the environmental load of the recycling process (1 t of recycled material in output).
- VIR is the environmental load of the production process of the virgin material (1 t in output).

The frequent use of the avoided burden approach can be justified by the difficulty of using the most common allocation criteria (by mass and economic value of product and co-product) in an appropriate way. On the other hand, the avoided burden approach currently used fails to distribute the environmental benefits in a fair way, since the environmental avoided burdens due to the replacement of primary material by the co-product are totally subtracted from the multifunctional process that generated the co-product, that is, the whole benefit is attributed only to the generating industry (SAADE, 2017).

In order to solve this issue, Saade (2017) proposed the avoided net impact approach (Equation 3). By applying this concept to the C&DW management, it can be considered that when the mineral fraction is recycled, the benefits obtained due to the avoided landfilling and transport are computed for the management system, and the benefits due to the avoided natural aggregate production and transport are computed for the productive sector that will use the recycled aggregate.

$$I_{liq} = I_{prod.subs.} - \left[I_{benef.co-prod.} + I_{other} - I_{FVD}\right] \qquad \text{(Equation 3)}$$

Where:

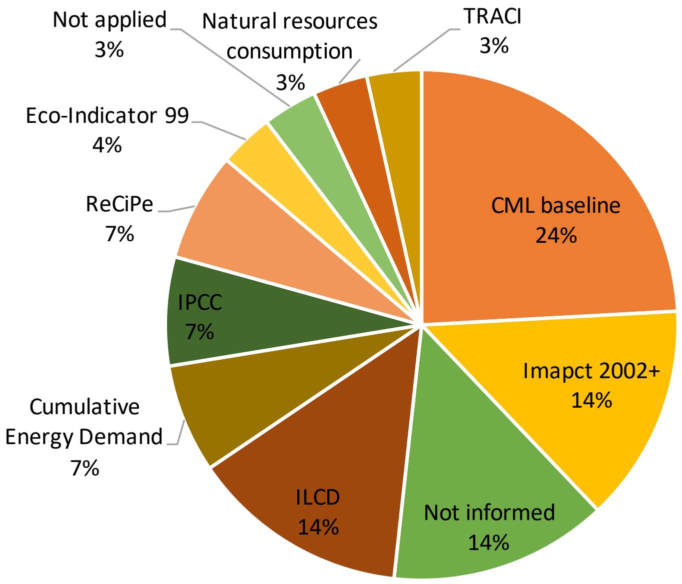
- I_{liq} avoided net impact, to be subtracted from the environmental impacts of the multifunctional process.
- $I_{prod.subs.}$ is avoided impact, associated with the raw material replaced by the co-product (which in the traditional approach is subtracted entirely from the multifunctional process).
- $I_{benef.co-prod.}$ impact associated with the co-product recycling.
- I_{FVD} is the impact associated with the final disposal of the co-product - if it is not used.
- I_{other} any charges that may arise due to the use of the co-product, for example, associated with transport if the co-product is not available locally.

The landfilling is compared to the recycling scenario in most of the studies, usually, it is considered that the mineral fraction is sent to inert landfills, while the non-mineral fraction is sent to specific landfills, such as sanitary landfill, or to incineration. It is important to note that most inventories rarely include leachate or gas emissions from mineral C&DW fraction disposed in inert landfills, since this fraction has a low content of pollutants, and can be considered chemically inert (DOKA, 2009). However, it is recommended that inventories consider such emissions, since a small percentage of biodegradable materials (wood, paper, cardboard, etc.) can be sent to inert landfills due to inefficiencies in the sorting process (BUTERA; CHRISTENSEN; ASTRUP, 2015).

In relation to the data source used in the inventory, in most cases, the C&DW composition and the general management information, such as the transport distances and the technology currently used, are obtained from primary data, based on documents or interviews with enterprises and/or public government. Some studies provide a detailed inventory for the mineral fraction recycling process, elaborated from primary data, which mainly include the consumption of diesel and electricity (BLENGINI; GARBARINO, 2010; MERCANTE *et al*., 2012; BORGHI; PANTINI; RIGAMONTI, 2018). Studies that do not have access to primary data, use data from the literature or databases; Ecoinvent is the most used both to complete the foreground data and to provide most of the background data.

Table A2.4 (Appendix A2) presents the life cycle impact assessment, optional LCIA elements, aspects considered in the sensitivity analysis and the software used by the studies. The most utilised LCIA methodology is the CML baseline, followed by the Impact 2002+ and the LCIA methodologies recommended by the ILCD (Figure 43). The objective and scope must report the selected LCIA methodology, however, four studies (14%) only informed the selected impact categories. Table A2.5 (Appendix A2) reveals that global warming impact category was selected by all studies, followed by acidification and eutrophication (61%); ozone layer depletion and photochemical ozone formation (48%); human toxicity (43%); respiratory inorganics (35%); resource depletion, non-renewable energy and freshwater ecotoxicity (26%), among others. Normalisation is the LCIA optional step most used by the studies, however, the majority analyse only the characterised impacts, probably, to avoid the uncertainties.

Figure 43. LCIA methodologies used in the LCA studies on C&DW management.



Source: Author (2019).

Sensitivity analysis evaluates the effect of a change on a single input in the final results of a LCA study. This analysis is performed during the interpretation, which the aims to evaluate the reliability of the final results and conclusions, determining how they will be affected by data uncertainties (ABNT, 2009b; BUENO *et al*., 2016).

The LCA studies of waste management have used various methods to performed an uncertainty analysis, without a systematic method (CLAVREUL; GUYONNET; CHRISTENSEN, 2012). The analysed studies evaluated the uncertainties by means of scenarios analysis where assumptions are changed one-at-a-time, variations on the transport distances, comparison between selective and traditional processes, recycling efficiency, among others.

SimaPro was the software most used by the LCA studies (52%). Other software used were LCAManager, US EPA Municipal Solid Waste Decision Support Tool, US EPA's WARM, WASTED model, EASETECH and Gabi. Only five studies (22%) have not used a software or not reported it.

Table A2.6 (Appendix 2) summarizes the main results and contribution of the studies to the decision makers and scientific community. C&DW recycling is the most recommended management alternative, followed by landfilling. However, some studies suggested that the mineral fraction recycling not always provide environmental benefits, since the production of high quality recycled aggregates depends on the waste quality, which means that the on-site sorting is the key factor to increase the benefits of recycling.

The crucial role of transport for the generated impacts is highlighted in all studies, mainly due to the high volume and mass of mineral fraction and long distances. In this context, all transport stages should be considered in specific LCA studies on C&DW management. The Geographical Information System is an important tool that can be used along with the LCA to model the transport stages based on reliable data.

The environmental benefits provided by the selective demolition differ among the studies. On the one hand, there is a consensus regarding to the benefits of on-site sorting, which increase the quality and quantity of wastes recovered and safely disposed. On the other hand, selective demolition may require an extra transport.

Prevention is the first priority in the waste management hierarchy, however, it is rarely considered in LCA studies. Currently, case studies that include waste prevention in LCA have presented significant avoided impacts, due to the elimination of some product and, consequently, reduction of waste generation (NESSI; RIGAMONTI; GROSSO, 2012). The quantification of environmental benefits from prevention in a LCA study requires knowledge of the waste management system and the product system to be avoided or replaced; that is because prevention is often related to modifications that could potentially have a greater impact than the ones provided by the wastes generated before the prevention activity occurred (LAURENT *et al*., 2014). However, there is no established procedure in standards and manuals on how to consider prevention in LCA studies of solid waste management.

Bizcocho and Llatas (2018) proposed two methodological approaches (option 1 and option 2) to include prevention scenarios in LCA studies of construction waste management, considering that "*prevention includes both the reduction of the amount and the degree of toxicity of the C&DW generated and the reduction of the adverse environmental impacts*". In this context, the C&DW prevention activities were classified into optimization measures (the components of the building elements are optimized; the amount of waste is reduced and the composition remains constant) and substitution measures (the building elements are replaced by other building elements without toxic materials or that generate less waste; the amount of waste and the composition vary).

To develop the methodological approaches some adjustments in the system boundary and functional unit were proposed (BIZCOCHO; LLATAS, 2018). In the option 1, the system boundary of prevention and non-prevention scenarios considered the upstream processes (those occurring during the production and construction stages) and the downstream processes (those related to the waste management, once generated). In the option 2, based on the "zero burden approach", therefore, the system boundary of prevention and non-prevention scenarios considered the downstream processes and, the upstream processes are only taken into account in prevention scenarios. The functional unit of both options was defined as "the management of the construction waste in a construction work which fulfills a given set of functions"; however, in option 1, the amount of construction waste managed can differ between prevention and non- prevention scenarios and, in option 2, it must be identical in all scenarios and equal to the baseline amount of construction waste generated in a non-prevention scenario. In addition, the authors applied the two methodological approaches in a case study, considering to the management of 1 tonne of concrete waste. The results showed that the prevention scenario provided a reduction of 60% of construction waste, as a consequence, the impacts were reduced in 60% in option 1 and 150% in option 2.

Among the four Brazilian dissertations that address the LCA applied to C&DW management (Table 9), only two comprise the four stages required in a LCA study. One of these studies, conducted by Barreto (2014), evaluated the management of 1 tonne of C&DW

considering the economic and environmental aspects, and three scenarios: sanitary landfill, landfill of C&DW Class A and inert waste, and recycling. The LCI was elaborated based on data collected from recycling, mining, landfill and sanitation companies, complemented by Ecoinvent database. The impacts were calculated using the CML 2001 (v3.0) baseline method, adapted by the Research Group on LCA (CICLOG) with the assistence of SimaPro 8.0 software. The results showed that recycling scenarios have the potential of avoiding 37% of economic costs and environmental impacts by up to 20% for abiotic depletion, 149% for global warming and 662% for energy demand.

Using the same functional unit, Rosado (2015) evaluated the environmental impacts of three C&DW management scenarios (landfilling, recycling and reuse) in the municipality of Limeira/SP. Primary data were obtained from interviews with the public government, visits in the management infrastructures and official documents, complemented by Ecoinvent database and literature. The results demonstradted that recycling is beneficial when efficient C&DW sorting takes place at construction sites, avoiding the transport of refuse to sorting and recycling facilities, and the distance between the generation source and the recycling unit is within 30 km.

The other two studies confirmed the feasibility of using LCA in the C&DW management. Pasquali (2005) used the iterativity aspect of the LCA methodology along with the principle of “continuous improvement” of Environmental Management System to propose improvements for the C&DW management in the municipality of Santa Maria/RS. The concepts were applied during the diagnosis of the current scenario, allowing the public government to implement some of the strategies proposed by the study and, at the same time, the results were evaluated and corrected when necessary.

Ferreira (2009) used Life Cycle Thinking in the analysis of the social, environmental and economic impacts of C&DW management in the Distrito Federal. The study compared the C&DW management system of Distrito Federal in relation to other municipalities with proper C&DW management, such as Belo Horizonte and São José do Rio Preto, and also to the international context (the Netherlands). The study concluded that the C&DW management in the Distrito Federal is conducted by a corrective approach with negative impacts in all stages. The Life Cycle Thinking assisted the identification of positive and negative impacts in the collection and transport stages, recycling, landfilling and illegal disposal of waste.

Table 9. Brazilian theses and dissertations about life cycle assessment studies related to construction and demolition waste.

Author (year)	University	Main goal of the thesis or dissertation	Main topic
Pasquali (2005)	UFSM	To utilise the LCA as a tool to assist the management of C&DW generated in Santa Maria (Rio Grande do Sul State).	LCA of C&DW management
Ferreira (2009)	UnB	To utilise the life cycle thinking as a support for C&DW management, based on the Distrito Feral, Belo Hozironte (Minas Gerais State), São José do Rio Preto (São Paulo State) and Netherlands case studies.	LCA of C&DW management
Santos (2010)	UNESP	To develop a comparative LCA study of different types of particle boards composed of agroindustrial residues manufactured at UNESP.	LCA of construction materials
Barreto (2014)	UFSC	To evaluate the environmental and economic performance of C&DW management scenarios in Brazil by means of the life cycle assessment and life cycle costing.	LCA of C&DW management
Pedroso* (2015)	UnB	To study the Energy LCA in the pre-use, use and demolition phases of a typical project of a social housing of 45,64 m² in Distrito Federal.	LCA of construction materials
Oliveira (2015)	USP	To estimate the consumptions of raw materials and water, embodied energy, emissions of CO_2 and solid wastes generated in the concrete blocks production based on the modular LCA.	LCA of construction materials
Rosado (2015)	UNICAMP	To develop and analyse a life cycle inventory of C&DW management systems, in order to identify the best alternatives to minimize environmental impacts.	LCA of C&DW management
Bento* (2016)	USP	To analyse the use of the LCA methodology to assist the decision making in structural projects of reinforced concrete, aiming at the improvement of environmental performance.	LCA of construction materials
Vinhal (2016)	UFSCar	To evaluate environmental indicators of ceramic blocks, based on LCA, from the extraction of raw materials (cradle) to the block production (gate), considering the Brazilian context.	LCA of construction materials
Coelho (2016)	UFES	To associate the production of self-compacting concrete with the incorporation of wastes and industrial by-products with the concept of life cycle, using the LCA methodology to make comparisons of mixtures in a specific scenario.	LCA of construction materials

Note: *Thesis.

3.3 REMARKS OF THE CHAPTER

The first section of this chapter presented a brief background of the LCA methodology and its application to evaluate the environmental performance of solid waste management systems. In addition, the main aspects of the four LCA stages are included in the section 3.2.

The last section presented a literature review based on 23 articles and 4 Brazilian dissertations, selected based on a systematic approach. The studies, published between 2010 and 2018, were analysed and discussed, taking into account the characteristics of the management system, the aspects of the LCA methodology and, the main results and contributions.

Specifically, the analysis of Table A2.2 and Table 8 showed the heterogeneity regarding to the main objective of the studies, waste management alternatives and waste composition. The analysis of Tables A2.3 and A2.4 revealed the absence of standardization in the use of the LCA methodology on C&DW management, mainly in relation to the system boundary definition, LCI elaboration and life cycle impact assessment methodology.

Usually, the collection of data for the LCI is considered one of the main limitations of the studies, due to the unavailability of specific and reliable sources of information. In addition to the absence of a standardization among the studies, some authors did not report important methodological aspects in the article, such as the functional unit and the used LCIA methodology.

In general, the results and contributions of the selected studies confirmed the LCA as a useful methodology to analyse the current environmental performance of the C&DW management, in order to determine the alternative management strategies, providing recommendations to the decision makers and scientific community.

CHAPTER

4

METHODOLOGY

The methodology comprises the following three main stages: (i) selection of the representative municipalities from Piracicaba, Capivari and Jundiaí Watershed; (ii) primary data gathering, and (iii) the methodological stages of the life cycle assessment study, namely “Goal and scope definition” and “Life cycle Inventory”.

4.1 REPRESENTATIVE MUNICIPALITIES OF THE STUDY AREA

The Piracicaba, Capivari and Jundiaí Watershed (PCJ Watershed) has 15,303 km² and comprises 58 municipalities from São Paulo State and 4 municipalities from Minas Gerais State (SHS, 2006). Tables 10 and 11 list the municipalities of São Paulo State totally and partially located in the PCJ watershed, respectively.

Table 10. Municipalities of São Paulo totally located in the PCJ Watershed.

Municipality	Area (km²)	Municipality	Area (km²)	Municipality	Area (km²)
Águas de São Pedro	3	Iracemápolis	105	Rafard	140
Americana	144	Itatiba	325	Rio Claro	521
Amparo	463	Itupeva	196	Rio das Pedras	221
Analândia	312	Jaguariúna	96	Saltinho	99
Artur Nogueira	192	Jarinu	200	Salto	160
Atibaia	478	Joanópolis	377	S. Bárbara	270
B. Jesus dos	120	Jundiaí	450	Santa Gertrudes	100
Bragança Paulista	489	Limeira	579	Santa Maria da	266
Cabreúva	267	Louveira	54	S.Antônio da	141
Campinas	887	Mombuca	136	São Pedro	596
Campo Limpo	84	Monte Alegre do	117	Sumaré	164
Capivari	319	Monte Mor	236	Tuiuti	128
Charqueada	179	Morungaba	143	Valinhos	111
Cordeirópolis	123	Nazaré Paulista	322	Vargem	145
Corumbataí	264	Nova Odessa	62	Várzea Paulista	36
Cosmópolis	166	Paulínia	145	Vinhedo	80
Elias Fausto	203	Pedra Bela	148		
Holambra	65	Pedreira	116		
Hortolândia	62	Pinhalzinho	161		
Indaiatuba	299	Piracaia	374		
Ipeúna	170	Piracicaba	1353		

Source: SHS (2006).

Table 11. Municipalities of São Paulo partially located in the PCJ Watershed.

Municipality	Area (km^2)	Municipality	Area (km^2)	Municipality	Area (km^2)
Anhembi	728	Itirapina	567	Serra Negra	203
Botucatu	554	Itu	642	Socorro	442
Cabreúva	267	Mairiporã	307	Tietê	398
Dois Córregos	599	Mineiros do Tietê	198	Torrinha	323
Engenheiro Coelho	112	Mogi Mirim	484		

Source: SHS (2006).

According to the "Diagnosis of Urban Solid Waste Management" (SNIS, 2015), the 58 municipalities from São Paulo State totally located in the PCJ watershed generated 1,877,274 tonnes of C&DW in 2013. Among them, 13 municipalities account for 96% of the total C&DW generation, which are highlighted in Table 12, and were the focus of this study.

Table 12. C&DW generation in tonnes/year of the municipalites of São Paulo totally located in the PCJ watershed and the representative municipalites highlighted.

Municipality	C&DW (t/year)	Municipality	C&DW (t/year)	Municipality	C&DW (t/year)
Águas de S.Pedro	3,216	Ipeúna	1,200	Piracaia	NI
Americana	NI	Iracemápolis	1,500	Piracicaba	180,672
Amparo	NI	Itatiba	NI	Rafard	NI
Analândia	80	Itupeva	92	Rio Claro	69,600
Artur Nogueira	11,000	Jaguariúna	13,200	Rio das Pedras	NI
Atibaia	84,950	Jarinu	20	Saltinho	NI
B. Jesus Perdões	NI	Joanópolis	576	Salto	40,389
Bragança Paulista	4,826	Jundiaí	147,018	Santa B. D'Oeste	20,000
Cabreúva	NI	Limeira	189,949	Santa Gertrudes	9,000
Campinas	792,001	Louveira	9,636	S. Maria da Serra	5
Campo Limpo Paulista	NI	Mombuca	NI	Santo Antônio da Posse	NI
Capivari	NI	Monte Alegre do Sul	NI	São Pedro	NI
Charqueada	30	Monte Mor	NI	Sumaré	86,000
Cordeirópolis	255	Morungaba	NI	Tuiuti	NI
Corumbataí	24	Nazaré Paulista	NI	Valinhos	NI
Cosmópolis	26,340	Nova Odessa	22,000	Vargem	2,400
Elias Fausto	650	Paulínia	NI	Várzea Paulista	NI
Holambra	7,640	Pedra Bela	NI	Vinhedo	414
Hortolândia	57,260	Pedreira	2,000		
Indaiatuba	90,931	Pinhalzinho	2,400		

Note: NI – not informed. Source: SNIS (2015).

4.2 PRIMARY DATA GATHERING OF THE REPRESENTATIVE MUNICIPALITIES

A questionnaire (Appendix A3) was elaborated for the primary data gathering about the C&DW management system, which was submitted to the Ethics Committee of UNICAMP; only after approval by the Committee, the questionnaire was applied to those responsible for the C&DW management system of each municipality.

The first contact was made by e-mail requesting a meeting with the sector responsible for the C&DW management system, then a telephone contact was made and, finally, the visit was carried out on the dates presented in Table 13. The municipalities agreed with the survey by signing the "Authorization for Data Collection" and the "Free and Informed Consent Form" (Appendix 3).

Table 13. Information on data gathering in selected municipalities carried out in 2016.

Municipality	Visit date	Position of the interviewee	Agency / Department / Secretary
Atibaia	26/04	Director of Solid Waste	SAAE (Environmental sanitation)
Campinas	01/06	Coordinator of the C&DW Recycling Facility	Secretary of Public Services
Cosmópolis	06/04	Technical director	Intermunicipal Consortium of Environmental Sanitation (CONSAB)
Hortolândia	05/04	Manager of the Environmental Inspection Sector	Secretary of Environment
Indaiatuba	23/05	Coordinator of Urban Solid Waste	Secretary of Urbanism and Environment
Jundiaí	15/06	Director of works, maintenance and waste	Secretary of Public Services
Limeira	26/12	Director of Environmental Education	Municipal Department of Rural Development and Environment
Nova Odessa	24/05	Director of Environmental Licensing and Inspection	Secretary of Environment
Piracicaba	10/05	Solid Waste Sector	Secretary of Defense of the Environment
Rio Claro*	19/05	Waste Control Manager	Secretariat of Planning, Development and Environment
Salto	24/04	Secretary of Environment	Secretary of Environment
Santa Bárbara D'Oeste	18/05	Environmental engineer	Secretary of Environment
Sumaré*	-	Superintendent	Intermunicipal Consortium for Solid Waste Management (CONSIMARES)

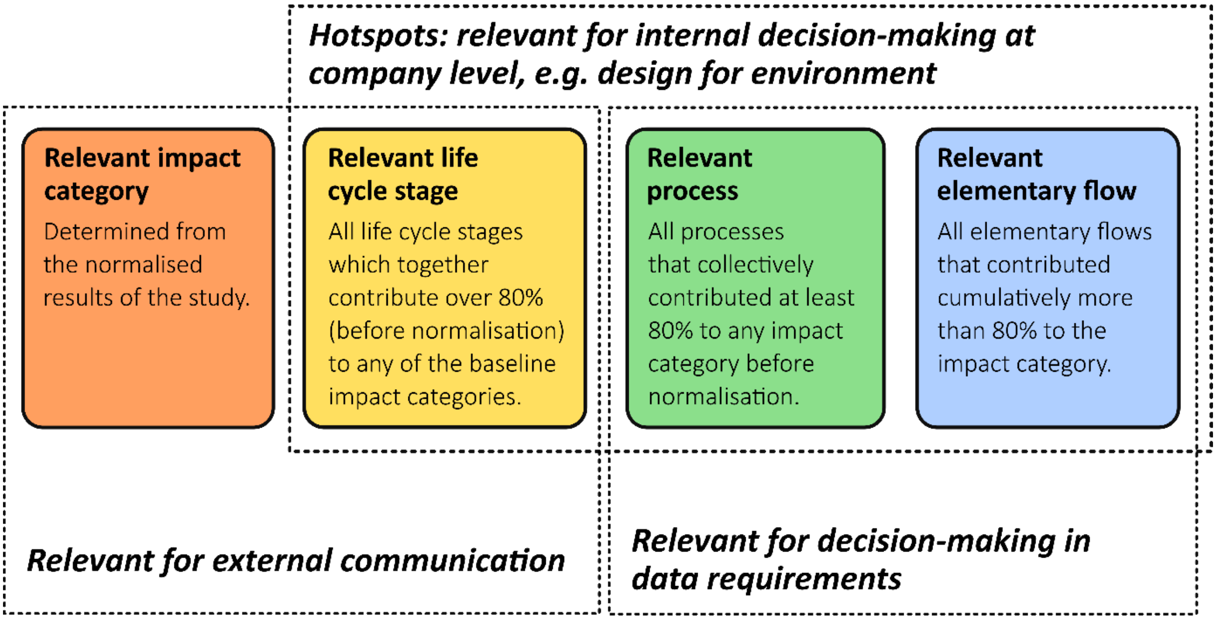
* The data on the C&DW management system of Rio Claro and Sumaré were obtained from their Solid Waste Management Plans and literature. Despite the visit in Rio Claro, the municipality did not answer the questionnaire. The Municipal Government of Sumaré requested that the interview be made with CONSIMARES, however, those responsible for the consortium was not available to schedule the visit.

4.3. LIFE CYCLE ASSESSMENT STUDY

The LCA study was developed in accordance with the requirements of ISO 14.040 and ISO 14.044 standards (ABNT, 2009a; 2009b), including its four major stages: (i) goal and scope definition, (ii) life cycle inventory, (iii) life cycle impact assessment and, (iv) interpretation. The first and second stages are related to the methodological aspects of the LCA study, and then, are presented in this chapter, while the third and fourth stages are presented in Chapter 5 (Result and Discussion).

In addition, this study follows the framework proposed by Zampori *et al*. (2016) for interpreting the LCA results, which are based on the Product Environmental Footprint guide elaborated by the European Commission (EC-JRC, 2017) to harmonize the application of LCA for evaluation of green products. Figure 44 reports the procedures used to identify the most relevant impact categories, life cycle stages, processes and elementary flows of the study.

Figure 44. Hotspot analysis procedure used in this study.



Source: adapted from Zampori *et al*. (2016).

4.3.1 GOAL AND SCOPE DEFINITION

4.3.1.1 INTENDED APPLICATION AND AUDIENCE

In order to improve the quality of water resources in areas of higher urban-industrial development, public policy proposals on water resource management began to emerge in Brazil in the early 90's. The watershed was adopted as a reference, aiming a regionalized management, conducted by watershed committees. As a result of this approach, the PCJ Watershed Committee was created in 1993, and so far it has been considered as an organizational model for the committees that have been created (BARBI, 2014).

According to the PCJ Watershed Plan 2010-2020, one of the requirements for recovering the water quality comprises studies to control diffuse sources of pollution caused by the absence or inefficiency in solid waste management systems (COBRAPE, 2011). Thus, it is important to evaluate the environmental performance of the current C&DW management system in this region, in order to propose alternative management scenarios.

In this context, the overall goal of this study is to evaluate the environmental performance of the C&DW management in the municipalities from PCJ Watershed, considering the current (base case scenario) and some alternative scenarios. The PCJ Watershed comprises 15,303 km², 58 municipalities belonging to the State of São Paulo (SP) and 4 to the State of Minas Gerais (MG) (SHS, 2006), and represents 0.18% of the Brazilian territory, 2.7% of the population and 6% of the GDP (COBRAPE, 2011).

This study considered thirteen municipalities, located in the State of São Paulo, which account for 35% of the total area, 87% of the inhabitants and 96% of the PCJ Watershed C&DW generation. Figure 45 and Table 14 report the main data of each municipality, including C&DW generation per capita in 2013 (latest reported data), proportion of C&DW generated (in tonnes) in relation to the functional unit[5], type and quantities of infrastructures used by the municipalities for the C&DW management in 2016.

The primary audience is that of the municipal departments responsible for the C&DW management and the PCJ Watershed Committee, both interested in assessing the environmental profile of current and alternative management scenarios. The results may also be useful to LCA practitioners and C&DW planners from other Brazilian regions, if adjustments in geographical, time and technology coverage are performed.

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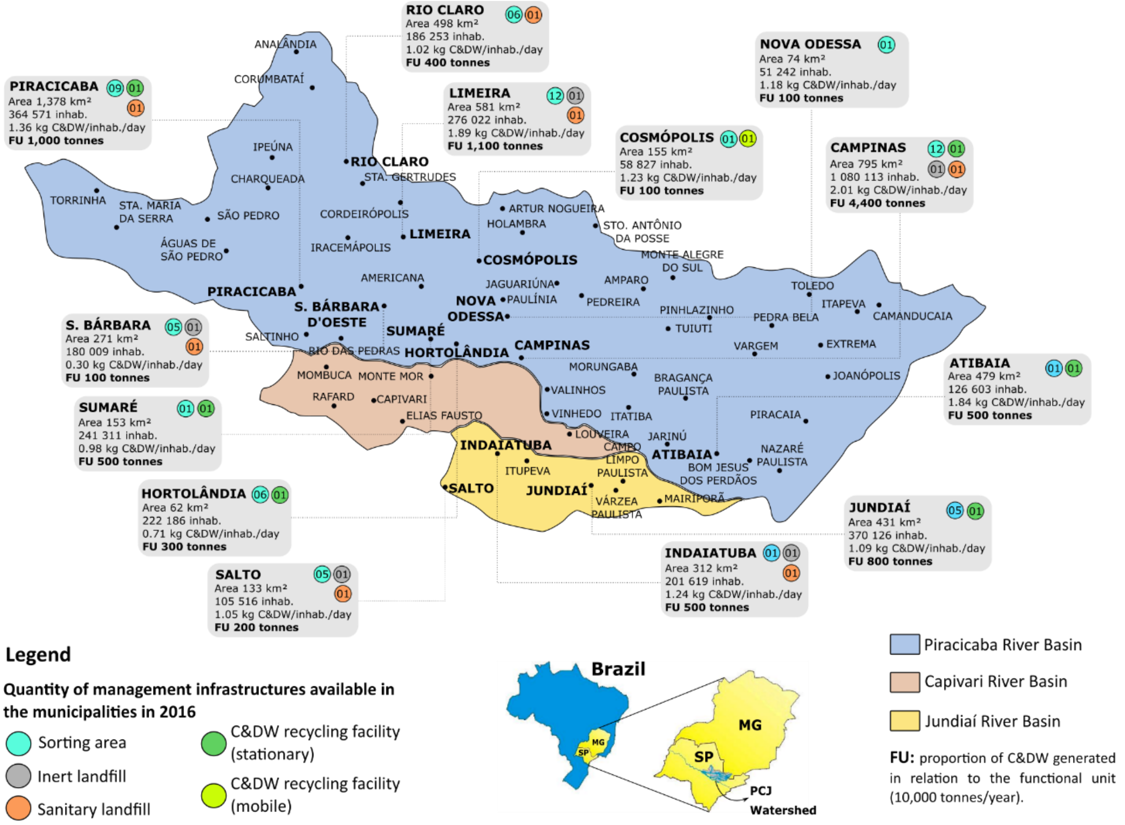
[5] This approach is explained in the section 5.2 – Life cycle inventory.

Figure 45. Study area (PCJ Watershed) and main data about the thirteen selected municipalities.



Source: Rosado *et al*. (2019).

Table 14. General data on the selected municipalities for this study.

Municipality	**Area¹ (km²)**	**Inhabitants²**	**C&DW³ (t/year)**	%	**C&DW (kg/inhabitants/day)**
Atibaia	479	126,603	84,950	5	1.84
Campinas	795	1,080,113	792,001	44	2.01
Cosmópolis	155	58,827	26,340	1	1.23
Hortolândia	62	222,186	57,260	3	0.71
Indaiatuba	312	201,619	90,931	5	1.24
Jundiaí	431	370,126	147,018	8	1.09
Limeira	581	276,022	189,949	11	1.89
Nova Odessa	74	51,242	22,000	1	1.18
Piracicaba	1,378	364,571	180,672	10	1.36
Rio Claro	498	186,253	69,600	4	1.02
Salto	133	105,516	40,389	2	1.05
Santa Bárbara D'Oeste	271	180,009	20,000	1	0.30
Sumaré	153	241,311	86,000	5	0.98
Total	**5,322**	**3,464,398**	**1,807,110**	**100**	**1.22***

Sources: ¹SEADE (2017). ²IBGE (2010). ³SNIS (2015). *Average C&DW per capita generation (kg/inhabitants/day).

4.3.1.2 THE SYSTEM UNDER ANALYSIS AND FUNCTIONAL UNIT

The system of interest comprises the C&DW management stages whose responsibility belongs to the municipal government. The functional unit was defined as the management of 10,000 tonnes of C&DW per year. The C&DW generation of the representative municipalities varies from 20,000 tonnes/year to 792,001 tonnes/year, therefore, this functional unit aims to assist the estimation of environmental impacts by means of a multiplication.

Only four municipalities have carried out C&DW characterisation studies (Table 15), by using different methodologies. The samples were collected in different management infrastructures, resulting in variations in the composition. The poor quality of composition data available in the selected municipalities of Atibaia, Limeira and Santa Bárbara suggested the utilisation of a different reference for this study. Data from Torrinha (which is not one of the thirteen selected municipalities, but belongs to the PCJ watershed) were used as reference, since they appear of high quality and have in any case a good geographical and time consistency.

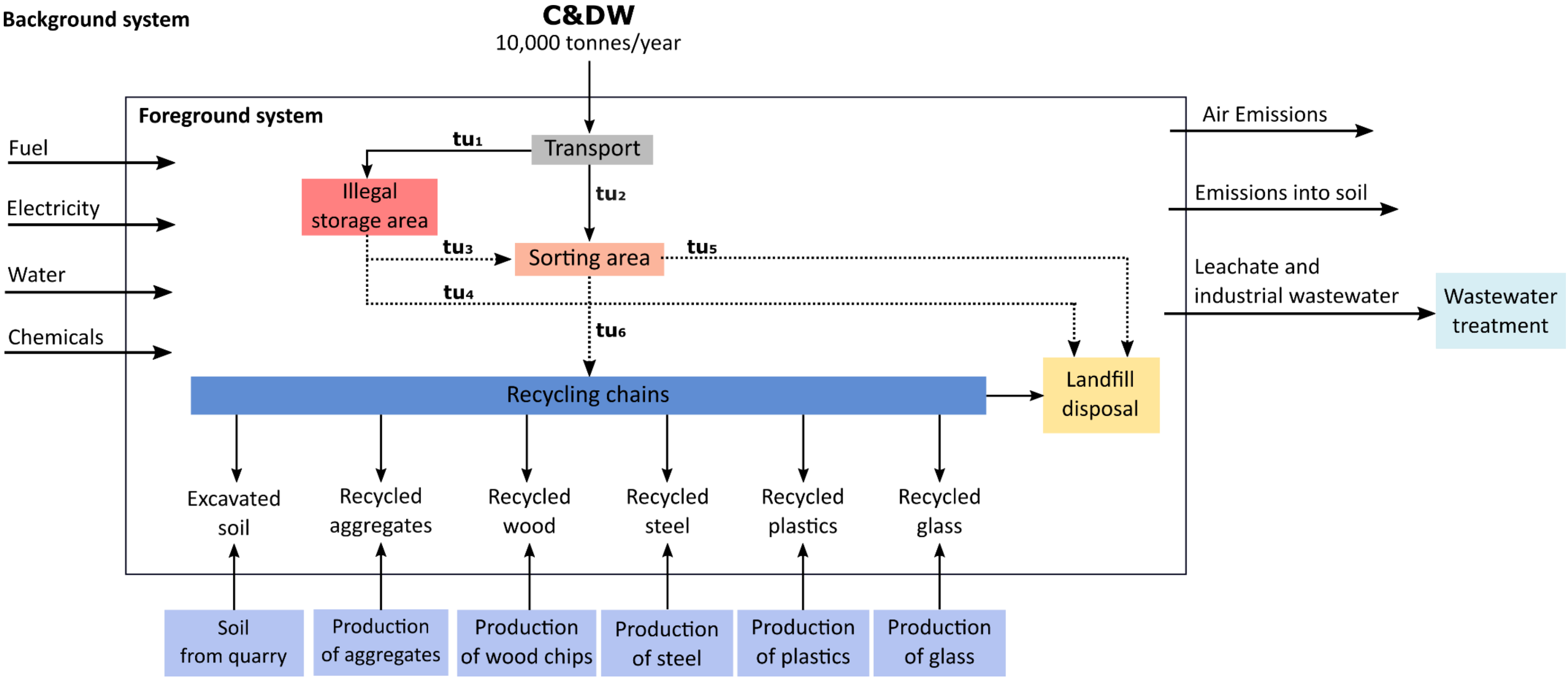
Table 15. Available data on C&DW composition (%) of municipalities from PCJ Watershed.

C&DW composition	**Type of Waste[1]**	**Atibaia[2]**	**Limeira[3]**	**Santa Bárbara[4]**	**Torrinha[5,*]**
MixC&DW	17 09 04	93.15	19.00	60.00	68.80
Excavated soil	17 05 04	0.35	50.34	20.00	18.10
Wood	17 02 01	0.42	4.66	10.00	3.70
Gypsum	17 08 02	0.82	-	-	-
Recyclable fraction		0.08	10.66	10.00	-
Iron and steel	17 04 05	-	-	-	3.20
Glass	17 02 02	-	-	-	1.70
Plastics	17 02 03	-	-	-	1.50
Paperboard	15 01 01	-	-	-	1.20
Mixed waste	20 03 01	5.18	15.34	-	1.80
Total		**100**	**100**	**100**	**100**

Notes: [1]Brazilian Waste Codes, which are equivalent to European Waste Codes. [2] Atibaia (2015). [3] Limeira (2015). [4] Santa Bárbara D'Oeste (2015). [5]Torrinha (2014). *Reference composition used in this study.

The official management infrastructures used by the municipalities comprise sorting areas, C&DW recycling facilities (stationary or mobile) and/or inert landfills. In addition, for the management of non-mineral C&DW fraction, it is necessary the use of different configurations of recycling facilities, as well as sanitary landfills (see Figure 45). The entire C&DW management activities, from the sorting areas or illegal storage areas, to its ultimate disposition were considered in the system boundaries (Figure 46), with the indication of the background and foreground systems.

Figure 46. System boundaries for the municipal C&DW management systems considered in this study, with the indication of the foreground and background systems. Dashed lines refer to the streams that have differences among the management systems analysed.



Source: Rosado *et al*. (2019).

4.3.1.3 TYPE OF LCA AND LCIA METHODOLOGY

The LCA study utilised an attributional approach and was developed with the support of SimaPro® 8.0.2 software. An attributional LCA aims at describing the potential environmental impacts of a system over its life cycle. This methodology uses historical, fact-based, measureable data of known uncertainty, and includes all the processes that significantly contribute to the system under study (EC-JRC, 2010).

The life cycle inventory was elaborated with most of the inputs from foreground system (fuel, electricity, water and other materials) obtained from official reports or technical visits to management infrastructures. The remaining inputs, direct, indirect and avoided burdens[6] were obtained from the literature and Ecoinvent v.3.1 database (2014), updated with Brazilian data where possible.

The allocation problem in the LCA model was avoided by using the system expansion method (also called “avoided burden” or “substitution”), in which the life cycle inventory of the processes or products replaced by the obtained co-products is subtracted from the analysed system (FINNVEDEN *et al*., 2009; EC-JRC, 2010).

In accordance with the literature review about LCA studies on C&DW, the most used methodologies are CML, Impact 2002+ and ILCD (see Figure 44). It is worth noting that ILCD methodology comprises recommendations for LCIA in the European context and Impact 2002+ has normalised factors only for European reference, while CML methodology provides normalised factors that covers the global environmental consequences.

The life cycle environmental impacts were evaluated by using CML baseline v.3.03 (GUINÉE *et al*., 2002) and Impact 2002+ v.2.12 (JOLLIET *et al.,* 2003). The lack of a specific LCIA methodology related to the Brazilian context (BUENO *et al*., 2016) suggested utilising both LCIA methodologies, making it possible to compare the obtained results and analyse the influence of the methodology.

CML methodology was developed at the University of Leiden in 2001, comprising a set of impact categories and characterisation methods for the impact assessment step (GUINÉE *et al*., 2002). Normalisation factors are provided for the following reference situations: Netherlands in 1997; West Europe in 1995; Europe in 2000 and World in 2000. The normalised results are presented in terms of person equivalent units; for the World reference,

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[6] Direct burdens – arising in the foreground waste management system (e.g. air emissions from vehicles). Indirect burdens – arising in the supply chains of materials and energy provided to the foreground (e.g. materials use and emissions arising from extraction and refining of transport fuels). Avoided burdens – associated with economic activities displaced by material and/or energy recovered from the waste (CLIFT; DOIG; FINNVEDEN, 2000).

one person equivalent represents the global average impact in the specific category associated with one person during one year (HUIJBREGTS *et al*., 2003).

Impact 2002+ methodology proposes a feasible implementation of a combined midpoint/damage approach. This methodology develops new concepts for the comparative assessment of human toxicity and ecotoxicity, and for other midpoint categories it adapts concepts from previous characterizing methods as Eco-indicator 99 and CML 2002 (JOLLIET *et al*., 2003). In addition, it has been frequently utilised in other studies of the same field (BLENGINI; GARBARINO, 2010; VITALE *et al*., 2017; ROSADO *et al*., 2017; HOSSAIN; WO; POON, 2017), suggesting that this methodology is adequate for this study. Normalisation can be performed at both midpoint and damage level, and the result is indicated as the number of equivalent persons affected during one year per unit of emission (person*year), in the European context.

Table 16 lists the midpoint impact categories utilised in the two LCIA methodologies, highlighting that, even though some impact categories have the same reference unit, only the categories of acidification and eutrophication have the same characterisation models.

Table 16. Midpoint impact categories and units used by Impact 2002+ and CML methodologies.

Impact 2002+ v2.12	**Unit**	**CML baseline v3.03**	**Unit**
Human toxicity (carcinogens, non-carcinogens)	kg chloroethylene eq	Human toxicity	kg 1,4-dichlorobenzene eq
Ozone layer depletion	kg CFC-11 eq	Ozone layer depletion	kg CFC-11 eq
Photochemical oxidation (respiratory organics)	kg ethylene eq	Photochemical oxidation	kg ethylene eq
Aquatic ecotoxicity	kg triethylene glycol eq	Fresh water aquatic ecotoxicity	kg 1,4-dichlorobenzene eq
		Marine aquatic ecotoxicity	kg 1,4-dichlorobenzene eq
Terrestrial ecotoxicity	kg triethylene glycol eq	Terrestrial ecotoxicity	kg 1,4-dichlorobenzene eq
Aquatic acidification	kg SO_2 eq	Acidification	kg SO_2 eq
Aquatic eutrophication	kg PO_4^{3-} eq	Eutrophication	kg PO_4^{3-} eq
Global warming	kg CO_2 eq	Global warming	kg CO_2 eq
Non-renewable energy	MJ primary	Abiotic depletion (fossil fuel)	MJ
Mineral extraction	MJ surplus	Abiotic depletion	kg Sb eq
Respiratory inorganics	kg $PM_{2.5}$ eq		
Ionizing radiations	Bq carbon-14 eq		
Terrestrial acidification/nitrification	kg SO_2 eq		
Land occupation	m²organic arable land		

Sources: Guinée *et al.* (2002) and Jolliet *et al.* (2003).

4.3.1.4 ASSUMPTIONS, LIMITATIONS AND DATA QUALITY

In the interviews with the responsible for the C&DW management municipal systems, it was observed that one of the main problems is the lack of control over the C&DW management flow. Hence, in Brazil it is common to elaborate Municipal Plans for Solid Waste Management based on data from the literature. Therefore, for this study, some data were estimated as detailed below.

a. Illegal storage areas

The illegal storage areas comprise some spots located usually in the periferic regions of the municipalities, where for different reasons the generators dispose of their C&DW and other wastes in a completely improper way. That happens because the scarce consciousness of the population regarding their responsabilities on the environmental quality maintenance, associated with insufficient technical and financial resources, and the weak supervision by the environmental control authorities. For this reason, the C&DW management system in Brazil, in different degrees, depending on the municipality, is mostly based on corrective actions. In such cases, the management basically involve the cleaning of illegal storage areas. The wastes removed from these areas are classified by a visual inspection, and depending on the composition, disposed of in an inert or sanitary landfill. There is anyway a clear absence of control on the quantities collected in the illegal storage areas.

According to the Municipal Plans for Solid Waste Management of Atibaia, Limeira and Piracicaba, the amount of C&DW sent to illegal storage areas are 66%, 10% and 43%, respectively. The other municipalities do not provide this information, therefore, this study assumed that, approximately, 30% of the C&DW generated in each municipality is sent to illegal storage areas, based on the Panorama of Solid Waste in Brazil of 2016 (ABRELPE, 2017).

The C&DW collection from illegal storage areas is done by using wheel loaders and trucks. Based on the average capacity of a wheel loader commonly used for this activity (3 m^3) and the C&DW density (1.5 t/m^3) (SINDUSCON-SP, 2015), it was estimated that this equipment manages 36 tonnes of C&DW/h. The consumption of diesel and lubricating oil of the wheel loader were obtained form primary data. The direct and indirect burdens derived from the processes “Diesel, burned in building machine {GLO}| processing | Alloc Def, U” and “Lubricating oil {RoW}| production | Alloc Def, U” of Ecoinvent v.3.1 (2014).

The distances from illegal storage areas to landfills were estimated based on primary data. The direct and indirect burdens of transport were calculated considering the process “Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| Alloc Def, U” of Ecoinvent v.3.1. (2014).

b. Sorting areas (drop-off sites)

The C&DW sorting is performed manually, then, for this stage only the transport and in some cases, wheel loader operation were considered. As aforementioned, the direct and indirect burdens derived from Ecoinvent v.3.1 (2014).

c. Transport phases

The sorting areas (drop-off sites), named as “Ecopontos”, receive up to 2 tonnes of C&DW per inhabitant per day, free of charge. The transport from generation source to sorting areas is done mostly by the generators by using their own cars, while the C&DW transport from the sorting areas to management infrastructures is done by trucks owned by the municipalities or contracted by them. The distances were estimated based on primary data, and the direct and indirect burdens of transport were obtained from the processes “Transport, passenger car, EURO 4 {RoW}| Alloc Def, U - tkm” and “Transport, freight, lorry 16-32 metric ton, EURO 4 {RoW}| Alloc Def, U” of Ecoinvent v.3.1. (2014).

d. Recycling rates (amount sent to recycling)

In most cases, the municipalities that have C&DW recycling facilities do not control the quantities of mineral fraction that are effectively recycled. Thus, based on data from a survey with Brazilian C&DW recycling facilities (ABRECON, 2015) it can be assumed a recycling rate of 20%. Table 17 lists the recycling rates of non-mineral fraction. The recycling rates for wood, iron and steel are based on the information gathered during the technical visits in the sorting areas, while the rates for plastics and glass were obtained in publications from Brazilian recycling associations. It was assumed that the paperboard is sent to landfill because of its poor quality.

Table 17. Recycling rates of non-mineral fraction.

Non-mineral fraction	Recycling rate (% in weight)	Source
Wood	90	Primary data
Iron and steel	95	Primary data
Plastics	22	Abiplast (2011)
Glass	47	Cempre (2011)

e. Recycling chains and avoided materials production

Table 18 lists the main data used for the life cycle inventory elaboration of the recycling processes. The inventory of transport stages was developed based on primary data about the distances. The direct and indirect burdens were obtained from the process “Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| Alloc Def, U” of Ecoinvent v.3.1. (2014). The complementary data are presented in the section 5.2 – Life cycle inventory.

Table 18. Main data used for the life cycle inventory elaboration of the recycling processes.

Process	**Data source**	**Avoided production**	**Data source**	**Substitution ratio**	**Data source**
Mineral fraction recycling	Primary data and Rosado *et al*. (2017)	Soil (20%)	Clay, clay pit operation[1,2,*]	1:1	Rosado *et al*. (2017)
		Sand and gravel (10%)	Sand, gravel and quarry operation[1,2,*]		
		Natural aggregate (70%)	Rosado *et al*. (2017)		
Wood recycling	Primary data and Rosado *et al*. (2017)	Wood chips	Wood chips, wet, measured as dry mass[1,2]	1:1	Rosado *et al*. (2017)
Plastics recycling	Ye *et al*. (2017)[*] and Perugini *et al*. (2005)[*]	PVC (52%)[4]	PVC, suspension polymerized, production[1,2,*]	1:0.81	Rigamonti *et al*. (2009)
		HDPE (29%); PET (11%) and PP (8%)[4]	HDPE/PET/PP, granulate production[1,2,*]		
Steel recycling	Steel production, electric, low-alloyed[1,2,*]	Primary steel (60%)[5]	Steel production, electric, low-alloyed[1,2,*]	1:0.98	Vitale *et al*. (2017) and WSA (2011)
		Secondary steel (40%)[5]	Steel production, converter, unalloyed[1,2,*]		
Glass recycling	Glass cullet, sorted , treatment of waste glass[1,2,*]	Glass production without cullet	Packaging glass, brown, production, without cullet[1,4,*]	1:0.82	Cremiato *et al*. (2017)

Notes: [1]Ecoinvent v.3.1 (2014). [2]RoW, Alloc Def, U. [3]GLO, Alloc Def, U. [4]Plastics composition based on Prestes *et al*. (2011). [5]Based on Vitale *et al*. (2017) and WSA (2011). *Updated with Brazilian energy mix.

f. Landfilling

The direct and indirect burdens from inert landfilling are only related to energy use for operation, as leachate emissions were not considered. This assumption appears reasonable since the waste material disposed in this type of landfill has a low pollutant content and is chemically inert to a large extent (DOKA, 2009). For the sanitary landfilling, the leachate emissions were considered. The following processes were used, which derived from Ecoinvent v.3.1 (2014): “Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Alloc Def, U”; “Inert waste {RoW}| treatment of, sanitary landfill | Alloc Def, U”; “Waste paperboard {RoW}| treatment of, sanitary landfill | Alloc Def, U” and, “Waste plastic, mixture {CH}| treatment of, sanitary landfill | Alloc Def, U (updated with Brazilian energy mix)”.

g. Capital goods

The skip bins and other types of containers used for the C&DW storage, the infrastructure and its maintenance, as well as the transport equipment maintenance, were not considered. This assumption is related to the lack of reliable data. Anyway, these burdens are almost similar for the considered alternatives, then the assumption will not affect the validity of final results.

4.3.1.5 BASE CASE AND ALTERNATIVE C&DW MANAGEMENT SCENARIOS

The base case scenario comprises the current C&DW management of the PCJ Watershed and assumes that 30% of the C&DW generated in each municipality is sent to illegal storage areas (ABRELPE, 2017)[7]. The waste removed from these areas are classified by visual inspection, and disposed of in inert or sanitary landfills, depending on their composition.

Seven municipalities recycle 20% of the mineral fraction (ABRECON, 2015), using different facilities (one mobile and six stationary recycling facilities with different configurations, as shown in Figure 46). Therefore, the type and quality of the produced recycled aggregates (RA) are different. Figure 48 reports the quantity of each type of RA produced and their uses in the base case scenario. Details about the recycling process of each municipality are presented in the section “4.3.2 – Life cycle inventory”.

The recycling rates for wood (90%), iron and steel (95%) have been based on the information gathered during the technical visits in the sorting areas, while the recycling rates for plastics (22%) and glass (47%) have been obtained from publications of Brazilian recycling associations (ABIPLAST, 2011; CEMPRE, 2011). It has been assumed that the paperboard is sent to landfill due to its poor quality.

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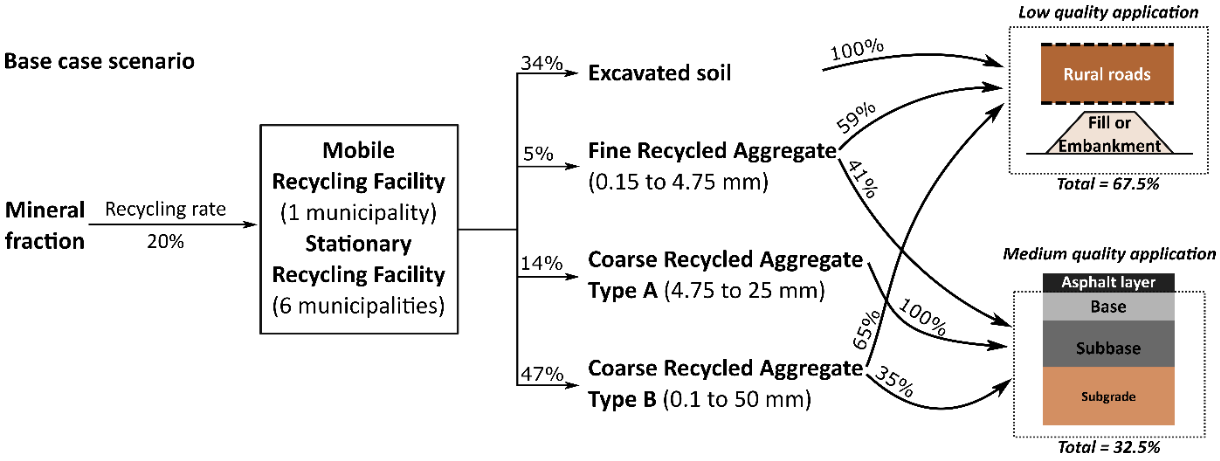
[7] With exception for Atibaia, Limeira and Piracicaba, where the amount of C&DW sent to illegal storage areas are 66%, 10% and 43%, respectively.

Figure 47. Overview of the mineral fraction recycling, in the base case scenario.



Source: Rosado *et al*. (2019).

The alternative management scenarios (Table 19) took into account the crucial role of mineral fraction, which accounts for 87% of C&DW composition, without modifications in other parameters, such as C&DW sent to illegal storage areas and recycling rates of wood, iron and steel, plastics and glass.

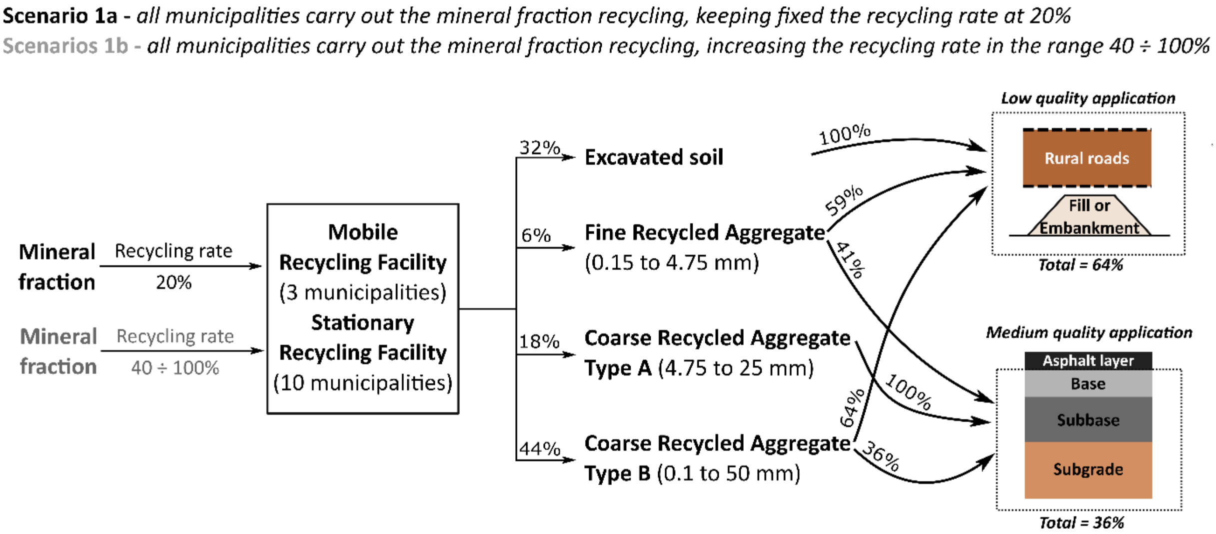
Table 19. Base case and alternative scenarios of mineral fraction management considered in this study.

Scenarios	Mineral fraction recycling rate (%)	Low quality recycled aggregate (%)	Medium quality recycled aggregate (%)
Base case	20	67.5	32.5
1a	20	64	36
1b	40 to 100	64	36
2a	20	43	57
2b	40 to 100	43	57
3.1a	20	64	36
3.1b	40 to 100	64	36
3.2a	20	64	36
3.2b	40 to 100	64	36

Notes: In the base case scenario, seven municipalities recycle the mineral fraction. In the alternatives scenarios it was assumed that all municipalities recycle the mineral fraction.

Scenario 1a considers that all municipalities recycle the mineral fraction, with a recycling rate of 20%. For the small-sized municipalities that do not have a recycling facility (Nova Odessa and Salto), it was assumed the use of a mobile recycling facility (Mobile RF) and the use of a stationary recycling facility (Stationary RF) for the other municipalities. The Mobile RF configuration was based on the equipment used by Cosmópolis, and the stationary facility configuration is described by Rosado *et al*. (2017). When all municipalities perform recycling, the amount of each RA produced and their uses are slightly different due to differences in the recycling facilities (Figure 48). In the **Scenarios 1b** the recycling rates increase from 20% to 100%, then assuming the values of 40%, 60%, 80% and 100%.

Figure 48. Overview of the mineral fraction recycling in the scenarios 1a and 1b.

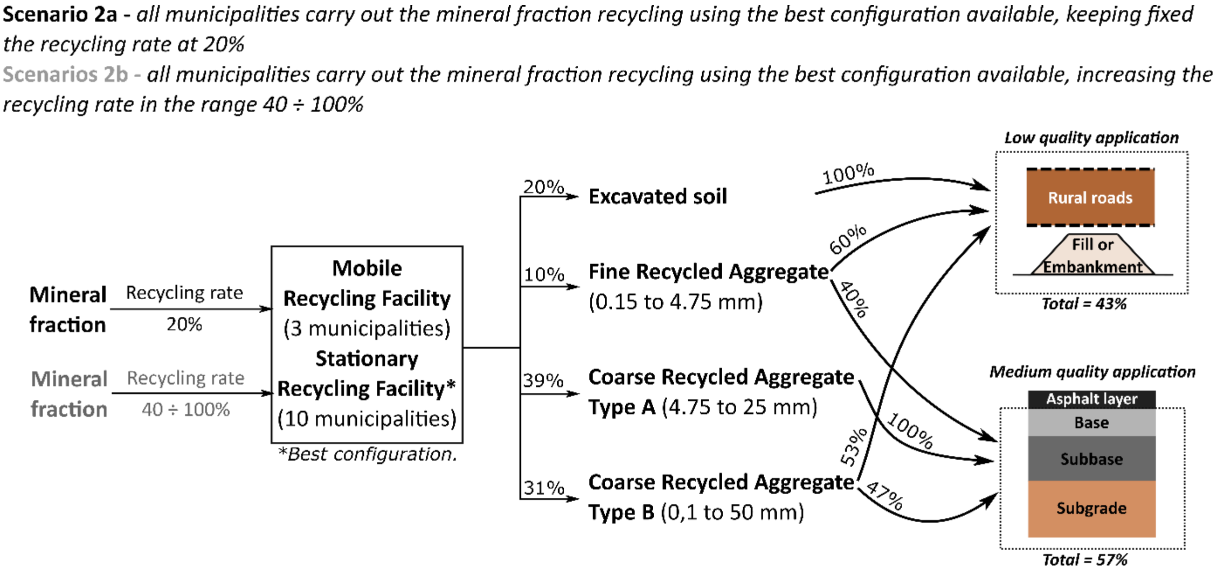

Scenario 1a - *all municipalities carry out the mineral fraction recycling, keeping fixed the recycling rate at 20%*

Scenarios 1b - *all municipalities carry out the mineral fraction recycling, increasing the recycling rate in the range 40 ÷ 100%*

Source: Rosado *et al*. (2019).

Scenario 2a considers that all Stationary RF utilised by the municipalities perform the recycling process by using the best RF configuration, obtaining a largest fraction of medium quality recycled aggregate (57%). **Scenarios 2b** consider the increase in recycling rates from 20% to 100%. Figure 49 shows the quantity of each type of RA produced and their uses in scenarios 2a and 2b.

Figure 49. Overview of the mineral fraction recycling in the scenarios 2a and 2b.

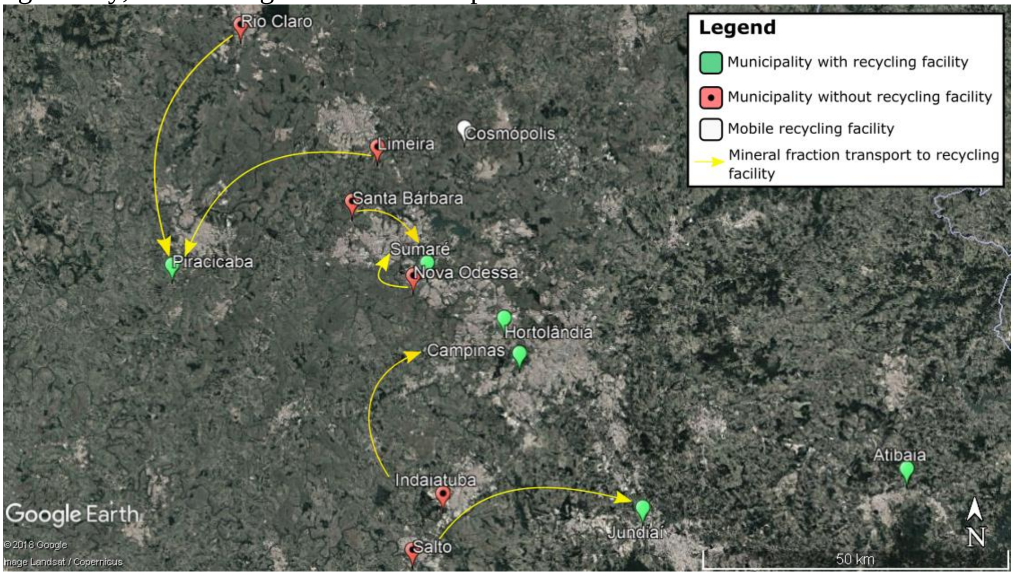

Scenario 2a - *all municipalities carry out the mineral fraction recycling using the best configuration available, keeping fixed the recycling rate at 20%*

Scenarios 2b - *all municipalities carry out the mineral fraction recycling using the best configuration available, increasing the recycling rate in the range 40 ÷ 100%*

Source: Rosado *et al*. (2019).

The scenarios 1 and 2 consider the existence of recycling facilities in the six municipalities that currently do not have such facilities, therefore, scenarios 3.1 and 3.2 assume that those municipalities use the recycling facilities of the nearest municipalities (Figure 50), in order to analyse the influence of the transport distances.

Figure 50. Indication of the recycling facilities that can be used by the municipalities that do not have a recycling facility, considering the shorter transport distances.



Source: adapted from Google Earth (2018).

Scenario 3.1a considers that all mineral fraction is transported to the existing recycling facilities, regardless of the recycling rate, following the same approach adopted in the base case scenario and alternative scenarios (1a, 1b, 2a and 2b); however, only 20% is recycled, and the remaining 80% is stored for future use. **Scenarios 3.1b** consider the increase in recycling rates from 20% to 100%.

Scenario 3.2a considers the transport of the mineral fraction that will be effectively recycled to the recycling facility (20%), the transport of the remaining mineral fraction to the inert landfill, and the environmental burdens of inert landfilling. **Scenarios 3.2b** consider the increase in recycling rates from 20% to 100%.

4.3.2 LIFE CYCLE INVENTORY

The inventory took into account a specific proportion of the C&DW generation rate of each municipality, with reference to the functional unit (10,000 tonnes), as indicated in Table 20. This approach aims to compensate the significant differences in the C&DW generation rates and management systems. For example, Campinas accounts for 44% of the C&DW generation of the PCJ Watershed, then, the LCI considers that 4,440 tonnes of C&DW are managed according to the management system of Campinas.

Table 20. Proportion of C&DW generation in each municipality related to the functional unit.

Municipality	C&DW generation (t/year)	%	Proportion of the functional unit (t)
Atibaia	84,950	5	500
Campinas	792,001	44	4,400
Cosmópolis	26,340	1	100
Hortolândia	57,260	3	300
Indaiatuba	90,931	5	500
Jundiaí	147,018	8	800
Limeira	189,949	11	1,100
Nova Odessa	22,000	1	100
Piracicaba	180,672	10	1,000
Rio Claro	69,600	4	400
Salto	40,389	2	200
Santa Bárbara D'Oeste	20,000	1	100
Sumaré	86,000	5	500
Total	**1,807,110**	**100**	**10,000**

4.3.2.1 INVENTORY OF TRANSPORT STAGES

The first stage refers to the C&DW transport from generation source to illegal storage areas (tu_1) or to sorting areas (tu_2). The urban area covered by each sorting area was determined by Google Earth Pro, defining a circle around it for estimating each delivery distante.

According to Pinto and González (2005), the average distance from C&DW generation to sorting area should be between 1.5 and 2.5 km. Then, the first radius was defined as 1.5 km and the percentage coverage was verified; if the value was less than 50% other radius was defined until the coverage of approximately 50% of the urban area. Thereafter, it was defined another radius obtaining approximately 100% of the urban area. Thus, according to the average of the radius required to serve approximately 50% and 100% of the urban area, it is possible to estimate the distance from the generation source to the sorting area.

For example, the municipality of Hortolândia has six storage areas and one C&DW recycling facility, which also receives C&DW from small generators. The radius of 1.5 km covers more than 50% of the urban area and the radius of 2.5 km covers approximately 100% of the urban area (Figure 51). Then, it was assumed an average distance from generation source to sorting areas of 2 km. This analysis was carried out for each municipality, taking into account 65 sorting areas.

The distance from generation source to illegal storage areas was assumed to be the same of that from generation source to sorting area, since both are located in the central region and peripheral regions throughout the municipalities.

Table 21 shows the complete set data set, including the delivery distances, the quantity of C&DW sent to illegal storage areas or to sorting areas, and the transport unit obtained by multiplying the transported quantity by the covered distance.

Figure 51. Coverage area of 1.5 km and 2.5 km of the sorting areas and C&DW recycling facility of the municipality of Hortolândia.

Source: adapted from Google Earth (2018).

Table 21. Transport from generation source to illegal storage areas (tu_1) and to sorting areas (tu_2).

Municipality	**Proportion of the functional unit (t)**	**C&DW quantity (t)^1**		**Distance (km)**		**Transport unit (tkm)**	
		Illegal areas	**Sorting areas**	**d_1**	**d_2**	**tu_1**	**tu_2**
Atibaia	500	330	170	12	12	3,960	2,040
Campinas	4,400	1,320	3,080	8	8	10,560	24,640
Cosmópolis	100	30	70	11	11	330	770
Hortolândia	300	90	210	2	2	180	420
Indaiatuba	500	150	350	10	10	1,500	3,500
Jundiaí	800	240	560	7	7	1,680	3,920
Limeira	1,100	110	990	3	3	330	2,970
Nova Odessa	100	30	70	7	7	210	490
Piracicaba	1,000	430	570	6	6	2,580	3,420
Rio Claro	400	120	280	4	4	480	1,120
Salto	200	60	140	3	3	180	420
Santa Bárbara	100	30	70	6	6	180	420
Sumaré	500	150	350	11	11	1,650	3,850
Total	**10,000**	**3,090**	**6,910**	**90**	**90**	**23,820**	**47,980**

Six municipalities send the C&DW preliminary stored in the illegal storage areas to sorting areas (transport distance tu_3), and the other municipalities send the waste to landfills (transport distance tu_4), as it has been sketched in Figure 46. Table 22 lists all the distances of interest.

Table 22. Transport from illegal storage areas to sorting areas (tu_3) or to landfill disposal (tu_4).

Municipality	C&DW collected in illegal storage areas (t)	d_3 (km)	d_4 (km)	tu_3 (tkm)	tu_4 (tkm)
Atibaia	330	9	0	2,970	0
Campinas	1,320	13	0	17,160	0
Cosmópolis	30	11	0	330	0
Hortolândia	90	8	0	720	0
Indaiatuba	150	0	10	0	1,500
Jundiaí	240	10	0	2,400	0
Limeira	110	0	12	0	1,320
Nova Odessa	30	0	19	0	570
Piracicaba	430	18	0	7,740	0
Rio Claro	120	0	18	0	2,160
Salto	60	0	6	0	360
Santa Bárbara	30	0	7	0	210
Sumaré	150	0	14	0	2,100
Total	**3,090**	**69**	**86**	**31,320**	**8,220**

Indaiatuba, Limeira, Nova Odessa, Rio Claro, Salto and Santa Bárbara D'Oeste send the mineral fraction to landfills, and Cosmópolis, Rio Claro, Salto and Sumaré send the wood to landfills. In all municipalities, paperboard and mixed waste are sent to sanitary landfills. It is important to note that the mixed waste includes the wood, steel, plastics and glass that are not recycled (see item 4.3.1.4-d). Table 23 presents the quantity of mineral fraction, wood, paperboard and mixed waste separated in the sorting areas and the transport distances to landfills.

Table 23. Transport from sorting areas to landfill disposal (tu_5).

Municipality	Quantity (t)				Distance (km)			Transport unit (tkm)			
	Mineral fraction	Wood	Paper board	Mixed waste	Mineral fraction	Wood	Paper/ Mixed waste	Mineral fraction	Wood	Paper board	Mixed waste
Atibaia	0	0	6	22	0	0	57	0	0	342	1,254
Campinas	0	0	53	194	0	0	14	0	0	742	2,716
Cosmópolis	0	4	1	5	0	30	30	0	120	30	150
Hortolândia	0	0	4	13	0	0	28	0	0	112	364
Indaiatuba	304	0	4	15	6	0	12	1,824	0	48	180
Jundiaí	0	0	10	35	0	0	58	0	0	580	2,030
Limeira	860	0	12	44	12	0	12	10,320	0	144	528
Nova Odessa	61	0	1	3	19	0	19	1,159	0	19	57
Piracicaba	0	0	12	44	0	0	82	0	0	984	3,608
Rio Claro	243	10	3	11	18	18	18	4,374	180	54	198
Salto	122	5	2	6	6	7	7	732	35	14	42
Santa Bárbara	61	0	1	3	7	0	7	427	0	7	21
Sumaré	0	13	4	14	0	14	14	0	182	56	196
Total	**1,651**	**32**	**113**	**409**	**68**	**69**	**358**	**18,836**	**517**	**3,132**	**11,344**

Table 24 shows the quantity of all C&DW fractions separated in the sorting areas and sent to recycling facilities. In the municipality of Atibaia the mineral fraction and wood are recycled within the sorting area; the same occurs for the mineral fraction in the municipality of Cosmópolis.

The data used to estimate all transport distances are shown in Table 25. The data based on real distance represents the distances calculated by Google Earth Pro, according to the information gathered by the questionnaires. The distances from sorting areas to recycling facilities were estimated considering the nearst recycling facility, since the municipalities do not have the control of the waste flow.

Table 24. Transport from sorting areas to recycling facilities (tu$_6$).

Municipalities	**Quantity (t)**					**Distance (km)**					**Transport unit (tkm)**				
	Mineral fraction	Wood	Steel	Plastics	Glass	Mineral fraction	Wood	Steel	Plastics	Glass	Mineral fraction	Wood	Steel	Plastics	Glass
Atibaia	435	17	15	2	4	0	0	154	55	69	0	0	2,310	110	276
Campinas	3824	147	134	15	35	13	129	99	20	119	49,712	18,963	13,266	300	4,165
Cosmópolis	87	0	3	0	0	0	0	57	0	0	0	0	171	0	0
Hortolândia	261	10	9	1	2	8	8	88	27	118	2,088	80	792	27	236
Indaiatuba	0	12	11	1	3	0	6	107	27	113	0	72	1,177	27	339
Jundiaí	695	27	24	3	6	6	6	122	44	77	4,170	162	2,928	132	462
Limeira	0	33	30	3	8	0	12	35	64	89	0	396	1,050	192	712
Nova Odessa	0	2	2	0	1	0	30	58	38	122	0	60	116	0	122
Piracicaba	869	33	30	3	8	18	53	63	103	146	15,642	1,749	1,890	309	1,168
Rio Claro	0	0	9	1	2	0	0	65	101	86	0	0	585	101	172
Salto	0	0	4	0	1	0	0	106	39	124	0	0	424	0	124
Santa Bárbara	0	2	2	0	1	0	30	45	59	124	0	60	90	0	124
Sumaré	304	0	11	1	3	3	0	59	35	116	912	0	649	35	348
Total	**6,475**	**283**	**284**	**30**	**74**	**48**	**274**	**1,058**	**612**	**1,303**	**72,524**	**21,542**	**25,448**	**1,233**	**8,248**

Table 25. Data source for the estimation of transport distances.

Municipalities	**Distance (km)** Generator to illegal areas	Generator to sorting areas	Illegal area to sorting areas	Illegal area to landfill	Mineral fraction to inert landfill	Mineral fraction to recycling	Wood to landfill	Wood to recyling	Steel to recycling	Plasctics to recycling	Glass to recycling	Paper to landfill	Mixed waste to landfill
	tu_1	**tu_2**	**tu_3**	**tu_4**	**tu_5**	**tu_6**	**tu_5**	**tu_6**	**tu_6**	**tu_6**	**tu_6**	**tu_5**	**tu_5**
Atibaia	12	12	9	0	0	0	0	0	154	55	69	57	57
Campinas	8	8	13	0	0	13	0	129	99	20	119	14	14
Cosmópolis	11	11	11	0	0	0	30	0	57	0	0	30	30
Hortolândia	2	2	8	0	0	8	0	8	88	27	118	28	28
Indaiatuba	10	10	0	10	6	0	0	6	107	27	113	12	12
Jundiaí	7	7	10	0	0	6	0	6	122	44	77	58	58
Limeira	3	3	0	12	12	0	0	12	35	64	89	12	12
Nova Odessa	7	7	0	19	19	0	0	30	58	38	122	19	19
Piracicaba	6	6	18	0	0	18	0	53	63	103	146	82	82
Rio Claro	4	4	0	18	18	0	18	0	65	101	86	18	18
Salto	3	3	0	6	6	0	7	0	106	39	124	7	7
Santa Bárbara	6	6	0	7	7	0	0	30	45	59	124	7	7
Sumaré	11	11	0	14	0	3	14	0	59	35	116	14	14
Total	**90**	**90**	**69**	**86**	**68**	**48**	**69**	**274**	**1,058**	**612**	**1,303**	**358**	**358**

Legend

🟨	Based on the real distance.
🟦	Estimated based on Google Earth Pro.
🟥	Non-existent stream.
⬜	No need for transport.
🟪	It was assumed equal to another distance.
🟩	Estimated data (the data were not provided by the municipality).

4.3.2.2 INVENTORY OF C&DW COLLECTION FROM ILLEGAL STORAGE AREAS

The C&DW from illegal storage areas is collected by a wheel loader, with capacity of 36 t/h, diesel consumption of 10 L/h and lubricating oil consumption of 0.165 kg/h (ROSADO *et al.*, 2017). Table 26 shows the data about the wheel loader operation for each municipality.

Table 26. Data about wheel loader operation used for the C&DW collection from illegal storage areas.

Municipality	**C&DW sent to illegal areas (t)**	**Wheel loader operation (hour)**	**Diesel consumption (L)**	**Lubricating oil consumption (kg)**
Atibaia	330	9	90	1.49
Campinas	1,320	37	370	6.11
Cosmópolis	30	1	10	0.17
Hortolândia	90	3	30	0.50
Indaiatuba	150	4	40	0.66
Jundiaí	240	7	70	1.16
Limeira	110	3	30	0.50
Nova Odessa	30	1	10	0.17
Piracicaba	430	12	120	1.98
Rio Claro	120	3	30	0.50
Salto	60	2	20	0.33
Santa Bárbara	30	1	10	0.17
Sumaré	150	4	40	0.66
Total	**3,090**	**87**	**870**	**14.40**

4.3.2.3 INVENTORY OF C&DW SORTING

Seven municipalities sort the C&DW by using a wheel loader similar to that used for collecting the waste from illegal storage areas (Table 27), but manual sorting is also performed. Then, based on technical visits in the sorting areas, it was assumed that 30% of the C&DW is sorted by using a wheel loader.

Table 27. Data on wheel loader operation used for the C&DW sorting.

Municipality	C&DW sent to sorting areas	C&DW from illegal area sent to sorting areas	Total	Wheel loader operation	Diesel consumption	Lubricating oil consumption
	(t)	(t)	(t)	(hour)	(L)	(kg)
Atibaia	170	330	500	4	40	0.66
Campinas	3,080	1,320	4,400	37	370	6.11
Cosmópolis	70	30	100	1	10	0.17
Hortolândia	210	90	300	3	30	0.50
Jundiaí	560	240	800	7	70	1.16
Piracicaba	570	430	1,000	8	80	1.32
Sumaré	350	0	350	3	30	0.50
Total	**5,010**	**2,440**	**7,450**	**63**	**630**	**10.42**

4.3.2.4 INVENTORY OF MINERAL FRACTION RECYCLING

In the base case scenario, seven municipalities recycle the mineral fraction using different facilities configurations, which produce different quantities of each recycled aggregate (Table 28). Table 29 presents the different use of the recycled aggregates generated in the recycling facilities, based on information gathered in the Solid Waste Management Plans and interviews with the representatives of municipalities.

Table 28. Recycled aggregates produced in the recycling facilities.

Municipality	Recycled material produced (% in weight)			
	Coarse RA Type A (4.75 to 25 mm)	**Coarse RA Type B** (0.10 to 50 mm)	**Fine RA** (0.15 to 4.75 mm)	**Soil excavation**
Atibaia	0.00	99.60	0.00	0.40
Campinas	4.94	46.75	2.06	46.25
Cosmópolis	0.00	60.00	0.00	40.00
Hortolândia	15.00	40.00	5.00	40.00
Piracicaba	30.00	40.00	20.00	10.00
Jundiaí	30.00	40.00	10.00	20.00
Sumaré	30.00	40.00	10.00	20.00

Table 29. Use of the recycled aggregates produced in the recycling facilities (% in weight).

Municipality	Coarse RA Type A	Coarse RA Type B		Fine RA		Soil excavation
	Medium	Medium	Low	Medium	Low	Low
Atibaia	0%	0%	100%	0%	0%	100%
Campinas	100%	40%	60%	50%	50%	100%
Cosmópolis	0%	0%	100%	0%	0%	100%
Hortolândia	100%	40%	60%	20%	80%	100%
Piracicaba	100%	40%	60%	40%	60%	100%
Jundiaí	100%	50%	50%	40%	60%	100%
Sumaré	100%	50%	50%	40%	60%	100%

Note: “medium” refers to medium quality application and “low” to low quality application.

Primary data from five C&DW recycling facilities were collected (Atibaia, Campinas, Cosmópolis, Hortolândia and Piracicaba). Available data of the other recyclinf facilities were not sufficient to elaborate a complete LCI. For this reason, data from Rosado *et al*. (2017) were used. Table 30 contains the productive capacity of the recycling facilities and data on the consumptions of diesel, lubricating oil, electricity and water (used for dust control) for the production of 1 tonne of recycled aggregate. It was assumed 5% of losses during the recycling process, which are disposed of in inert landfills; with the exception of the municipality of Cosmópolis, where losses remain at the site.

Table 30. Productive capacity of recycling facilities and data about materials and energy consumption for the production of 1 tonne of recycled aggregate.

Municipality	Productive capacity (t/h)	Materials and Energy consumption			
		Diesel (L/t)	Lubricating oil (kg/t)	Electricity (kWh/t)	Water (L/t)
Atibaia	20	0.35	0.003	0.88	0.40
Campinas	70	0.61	0.008	3.22	1.40
Cosmópolis	45	0.63	0.0009	-	0.34
Hortolândia	45	0.35	0.003	2.94	0.90
Piracicaba	35	0.34	0.002	2.80	0.70
Jundiaí	40	0.35	0.003	2.54	0.80
Sumaré	40	0.35	0.003	2.54	0.80

4.3.2.4.1 RECYCLING FACILITY OF ATIBAIA

The recycling facility used by the municipality of Atibaia has a productive capacity of 20 t/h, which comprises 99.60% of coarse RA and 0.40% of soil excavation. Figure 52 shows the recycling process and Table 31 lists the data related to the equipments.

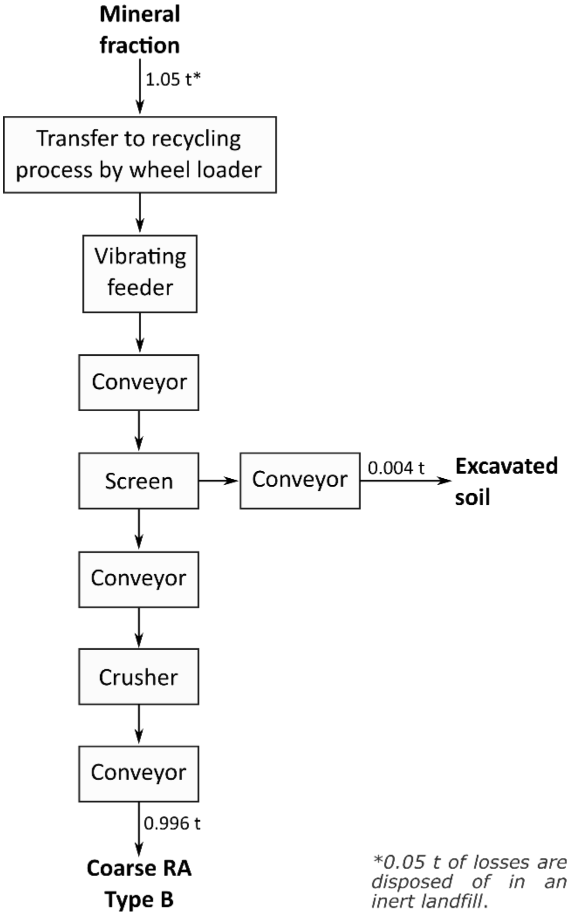
Energy consumption is calculated by multiplying the power rating of each equipment by the operation hour required to produce 1 tonne of RA. Then, the recycling of 1 tonne of RA consumes 0.88 kWh.

The wheel loader used to transfer the mineral fraction to the vibrating feeder has a bucket capacity of 3 m³ and rated net power of 116 kW. It was calculated that in one hour it is possible to handle 24 m³ of material, which corresponds to 36 t (density of 1.5 t/m³). For an average diesel consumption of 0.20 L/kWh, for wheel loader operating in a medium intensity (55% of the net power), it was obtained a diesel consumption of 12.71 L/h. The lubricating oil consumption was calculated based on the information available in the study of Rosado *et al.* (2017), that is 0.125 kg/h.

Table 31. Data related to equipment used in the mineral fraction recycling facility of Atibaia.

Equipment	Power (kW)	Quantity	Total Power (kW)
Vibrating feeder	2.21	1	2.21
Conveyor	2.21	4	8.84
Screen	2.21	1	2.21
Crusher	4.42	1	4.42
Total	**11.05**	**7**	**17.68**

Figure 52. Process of the mineral fraction recycling in the municipality of Atibaia.



Source: Author (2019).

4.3.2.4.2 RECYCLING FACILITY OF CAMPINAS

In the recycling facility of Campinas, the mineral fraction is classified in grey (concrete, asphalt, gravel, tiles without asbestos) and red (ceramic tiles, bricks, soil, and others). The two types of waste are recycled separately as shown in Figure 53. The grey fraction recycling produces three different types of coarse RA type A, one type of fine RA and one type of coarse RA type B. The recycling of the red fraction produces excavated soil and coarse RA type B.

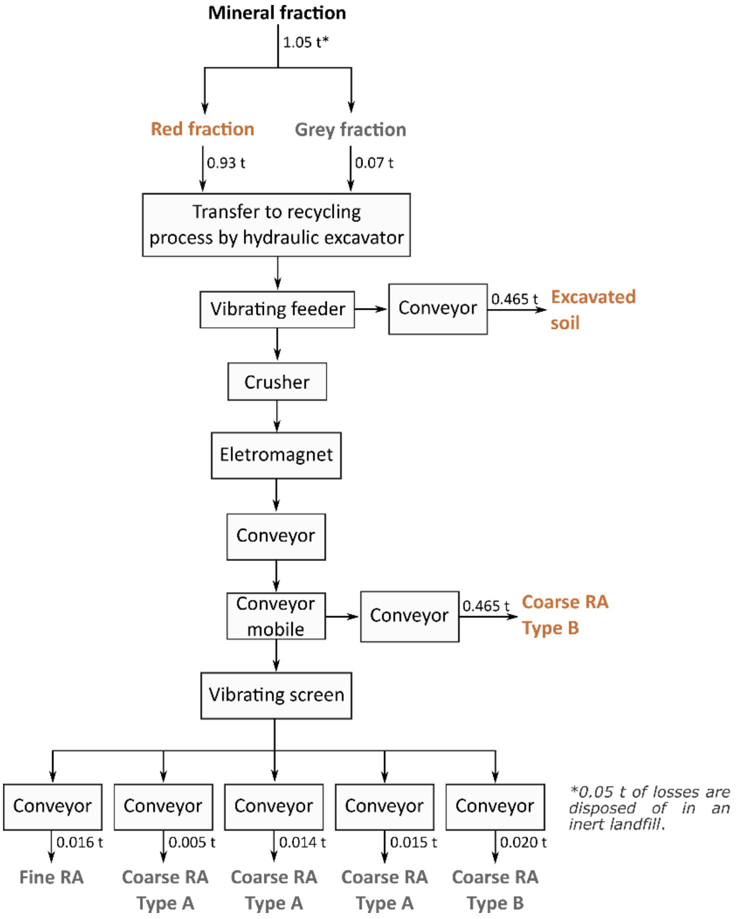
It is important to note that the recycling of grey and red fractions does not occur simultaneously, because there is only one vibrating feeder and one crusher. Then, when the grey fraction is recycled, the mobile conveyor is linked with the vibrating screen. According to the total equipment power presented in Table 32, and considering that the productive capacity is 70 t/h, the electricity consumption for the recycling of 1 tonne of RA is 3.22 kWh.

The hydraulic excavator used to transfer the mineral fraction to vibrating feeder has bucket capacity of 1.8 m³ and rated net power of 110 kW. It was calculated that in one hour it is possible to handle 14.4 m³ of material, which corresponds to 21.6 t (density of 1.5 t/m³). Using the same approach aforementioned, it was found that the hydraulic excavator consumes 12.21 L of diesel/h and 0.125 kg of lubricating oil/h.

Table 32. Data related to equipment used in the mineral fraction recycling facility of Campinas.

Equipment	Power (kW)	Quantity	Total Power (kW)
Vibrating feeder	22.37	1	22.37
Crusher	111.86	1	111.86
Vibrating screen	14.91	1	14.91
Electromagnet	1.49	1	1.49
Conveyor (mobile)	5.59	1	5.59
Conveyor	5.97	2	11.94
Conveyor	5.59	1	5.59
Conveyor	11.93	4	47.72
Anti-dust system	3.73	1	3.73
Total	**183.44**	**13**	**225.20**

Figure 53. Process of the mineral fraction recycling in the municipality of Campinas.



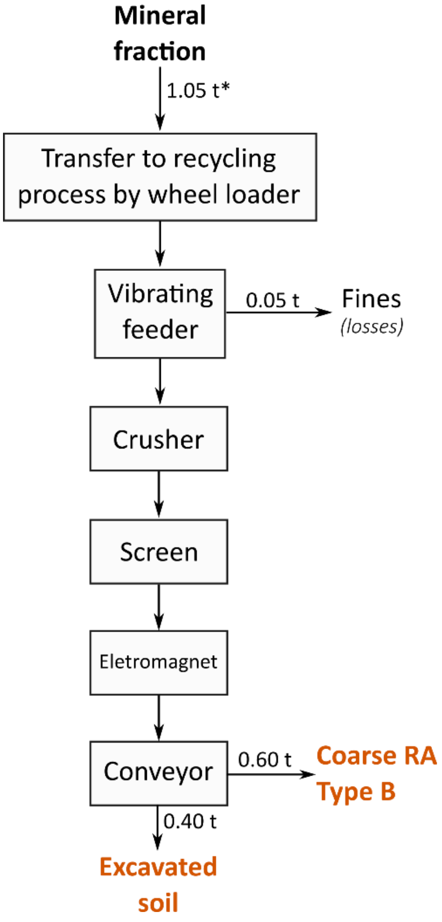
**0.05 t of losses are disposed of in an inert landfill.*

Source: Author (2019).

4.3.2.4.3 RECYCLING FACILITY OF COSMÓPOLIS

The mineral fraction is recycled by using two mobile recycling facilities, whose productive capacity is 45 t/h. In the recycling process, the waste is transferred to a vibrating feeder by a wheel loader, then the material is comminuted in an impact crusher and follows to a magnet conveyor (Figure 54). This type of recycling facility produces approximately 40% soil excavation and 60% coarse RA type B. Table 33 shows the average production in ton per day (t/d) and data about diesel, lubricating oil and water consumption per day (L/d or kg/d) and per tonne of RA (L/t or kg/t) produced.

Figure 54. Process of the mineral fraction recycling in the municipality of Cosmópolis.



Source: Author (2019).

Table 33. Data on mobile recycling facilities operation in 2016 in the municipality of Cosmópolis.

Mobile recycling facility	Total production (t/y)	Average production (t/d)	Diesel consumption (L/d)	(L/t)	Lubricating oil consumption (kg/d)	(kg/t)	Water consumption (L/d)	(L/t)
1	1935	194.49	60	0.31	0.14	7.20E-04	50	0.26
2	11,445	142.88	40	0.28	0.14	9.80E-04	50	0.35

Considering that the mobile recycling facility 1 was responsible for 15% of the total recycled aggregates produced in 2016 and the mobile recycling facility 2 accounted for 85%, the average consumption per ton are 0.28 L of diesel, 9.41E-04 kg lubricating oil and 0.34 L of water (used for dust control). For the wheel loader it was assumed the same type used in the recycling facility of Atibaia (capacity of 3 m³ and rated net power of 116 kW).

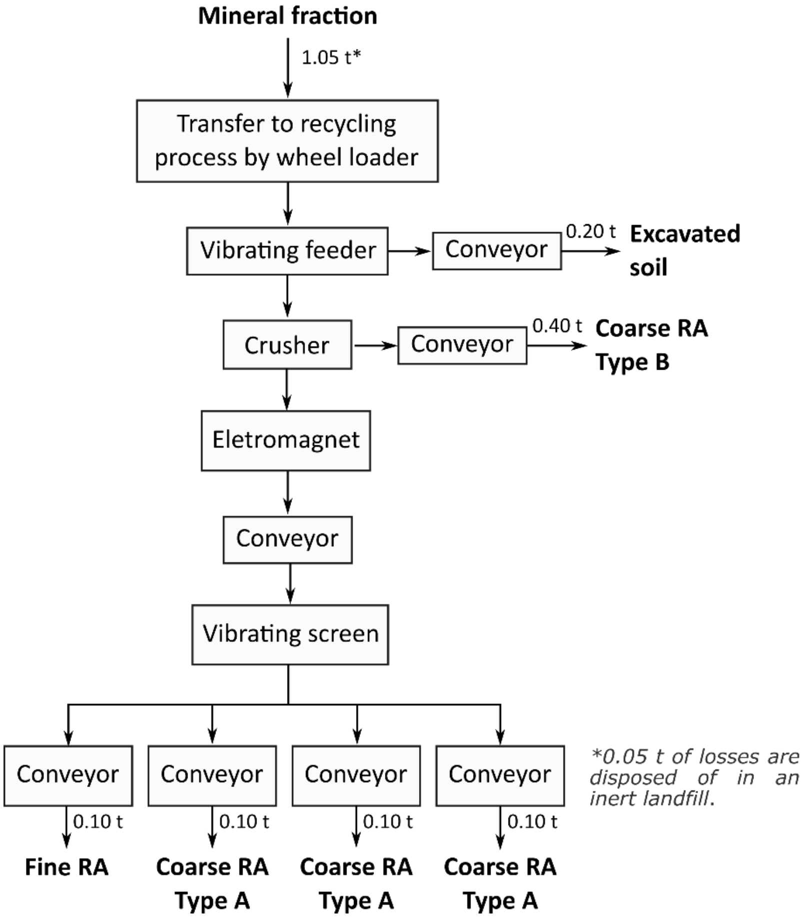
4.3.2.4.4 RECYCLING FACILITY OF HORTOLÂNDIA

The recycling facility of Hortolândia has a productive capacity of 45 t/h and uses the equipments listed in Table 34. The quantity produced of each recycled aggregate was not informed by the facility, then, the values indicates in Figure 55 were estimated. For the wheel loader it was assumed the same type used in the recycling facility of Atibaia (capacity of 3 m³ and rated net power of 116 kW).

Table 34. Data related to equipment used in the mineral fraction recycling facility of Hortolândia.

Equipment	Power (kW)	Quantity	Total Power (kW)
Vibrating feeder	3.68	1	3.68
Crusher	106.28	1	106.28
Vibrating screen	5.52	1	5.52
Electromagnet	0.74	1	0.74
Conveyor	1.47	5	7.35
Conveyor	2.94	1	2.94
Conveyor	3.68	1	3.68
Anti-dust system	2.21	1	2.21
Total	**126.52**	**11**	**132.40**

Figure 55. Process of the mineral fraction recycling in the municipality of Hortolândia.



Source: Author (2019).

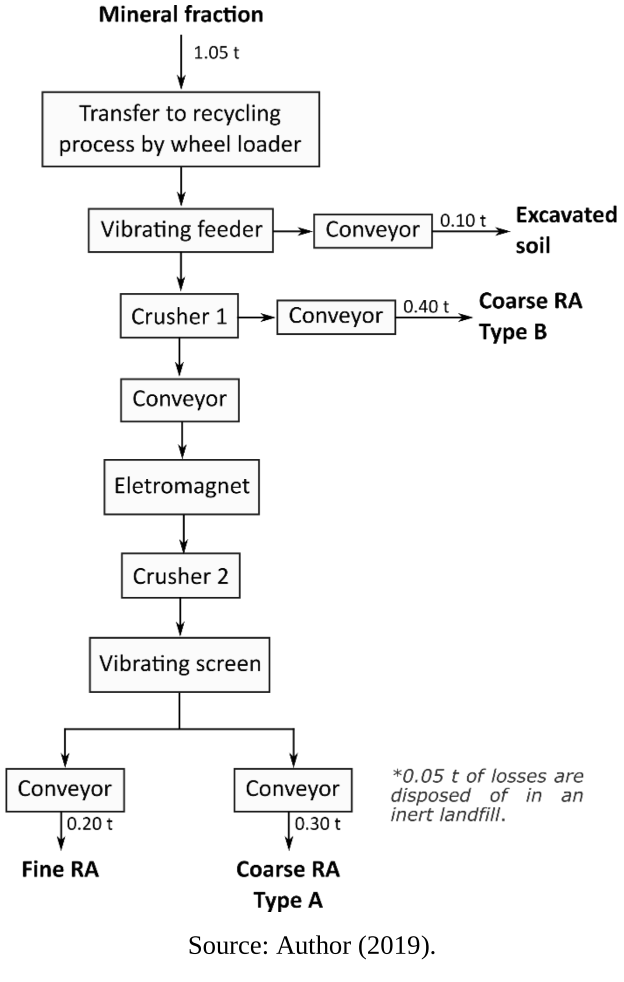
4.3.2.4.5 RECYCLING FACILITY OF PIRACICABA

The recycling facility of Piracicaba has a productive capacity of 35 t/h, it uses the equipment listed in Table 35 according to the process presented in Figure 56. It was informed that the wheel loader consumes an average of 12 L of diesel/h and 0.069 kg of lubricating oil/h; and has the capacity of 3 m³ (one hour it is possible to handle 24 m³ of material, which corresponds to 36 t).

Table 35. Data related to equipment used in the mineral fraction recycling facility of Piracicaba.

Equipment	Power (kW)	Quantity	Total Power (kW)
Vibrating feeder	7.35	1	7.35
Crusher 1	18.39	1	18.39
Conveyor	2.21	5	11.05
Electromagnet	2.21	1	2.21
Crusher 2	55.16	1	55.16
Vibrating screen	3.68	1	3.68
Total	**89.00**	**10**	**97.84**

Figure 56. Process of the mineral fraction recycling in the municipality of Piracicaba.



Source: Author (2019).

4.3.2.4.6 RECYCLING FACILITIES OF JUNDIAÍ AND SUMARÉ

Data on the equipment power and productive capacity of the recycling facilities of Jundiaí and Sumaré were not available, then it was assumed the life cycle inventory elaborated by Rosado *et al*. (2017).

4.3.2.5 INVENTORY OF NON-MINERAL FRACTION RECYCLING

Data for the life cycle inventory of non-mineral fraction recycling were obtained from literature and from Ecoinvent v.3.1 (2014) database, with exception for those related to wood recycling, whose data were collected in technical visits and updated with data from Rosado *et al*. (2017). Table 36 presents the data source used to elaborate the LCI of recycling processes and the respective efficiencies, determined by multiplying the sorting and reprocessing efficiencies reported in the analysed studies.

Table 36. Data source of life cycle inventory of non-mineral fraction recycling and efficiencies.

Non-mineral fraction	LCI of recycling process	Efficiency of sorting stage (A) (% in weight)	Efficiency of reprocessing stage (B) (% in weight)	Recycling efficiency (AxB) (% in weight)
Wood	Primary data and Rosado et al. (2017)	70.0	95.0	66.5
Steel	WSA (2011) and Ecoinvent v. 3.1 (2014)	90.5	100.0	90.5
PVC (52%)	Ye *et al*. (2017)	93.6	97.1	90.9
HDPE (29%)	Perugini *et al*. (2005)	75.0	88.0	66.0
PET (11%)	Perugini *et al*. (2005)	75.0	76.0	57.0
PP (8%)	Perugini *et al*. (2005)	75.0	88.0	66.0
Glass	Ecoinvent v. 3.1 (2014)	85.0	100.0	85.0

4.3.2.5.1 INVENTORY OF WOOD RECYCLING

Wood waste after grinding (recycled wood chips) can be used as feedstock in biomass combustion systems (with temperature above 750°C) and in industrial wood production (SINDUSCON-SP, 2015). According to the technical visits, the recycled wood chips are commonly used as biomass fuel.

Generally, the wood waste arrives to the recycling facility mixed with other materials such as concrete, mortar, metals and mold release agents for concrete (SINDUSCON-SP, 2015). Based on the study of Costa (2007), it was assumed the efficiency of sorting stage as 70%; while the efficiency of reprocessing was assumed to be 95%, based on the technical visits.

Although nine municipalities recycle the wood, only data related to the recycling process carried out in Hortolândia are available. For the other municipalities it was utilised the inventory reported in the study of Rosado *et al*. (2017), since this study was based on data from a wood recyclinf falicity located in the São Paulo State. Table 37 presents the equipment used, and Table 38 contains the productive capacity of wood recycling facilities and data on materials and energy consumption for the production of 1 tonne of recycled wood chips.

The backhoe loader used to transfer the wood to the recycling process consumes an average of 7.5 L of diesel/h and 0.122 kg of lubricating oil/h; and it has a capacity of 1.8 m³. It was estimated that in one hour it is possible to handle 14.4 m³ of material, which corresponds to 3.02 tonnes (density of 0.21 t/m³).

Table 37. Data about the equipments used in the wood recycling processes.

Municipality	Equipment	Power (kW)	Quantity	Total Power (kW)
Hortolândia	Cutter	147.00	1	147.00
Other municipalities	Pre-cutter	36.77	1	83.84
	Conveyor	5.15	1	
	Cutter	36.77	1	
	Conveyor	5.15	1	

Table 38. Productive capacity of wood recycling facilities and data about the materials and energy consumption for the production of 1 ton of recycled wood chips.

Municipality	Productive capacity (t/h)	Materials and Energy consumption		
		Diesel (L/t)	Lubricating oil (kg/t)	Electricity (kWh/t)
Hortolândia	60	2.48	0.04	2.45
Other municipalities	10	2.48	0.04	8.38

4.3.2.5.2 INVENTORY OF STEEL RECYCLING

The steel scrap from construction and demolition waste, classified as post-consumer scrap, requires a previous process before its use for steel production. These processes mainly comprise scrap shredding, reduction of impurities and adequacy of contaminant content (WSA, 2011; BATISTA, 2014).

The iron and steel scraps can be recycled by two processes, basic oxygen furnace (BOF) or electric arc furnace (EAF). The EAF process is the main technology used for steel scrap recycling because it can receive 100% of scraps, while the BOF process only accepts 25 to 30% of steel scrap (DAMGAARD; CHRISTENSEN, 2010). Direct and indirect burdens of steel recycling were obtained from the process “Steel, low-alloyed {RoW}| steel production, electric, low-alloyed | Alloc Def, U” of Ecoinvent v. 3.1 (2014) database updated with Brazilian energy mix.

4.3.2.5.3 INVENTORY OF PLASTICS RECYCLING

The composition of plastic waste was assumed as 52% of PVC, 29% of HDPE, 11% of PET and 8% of PP, based on Prestes *et al*. (2012). Plastic waste are recycled by mechanical processes, which comprise manual sorting, grinding, washing, drying and processing into granules (ABIPLAST, 2017). Data from Brazilian plastics recycling industries were not found in the literature, then, LCI data were obtained from the study of Ye *et al*. (2017) for PVC recycling and from the study of Perugini, Mastellone and Arena (2005) for the recycling of other plastics. Both LCIs were updated with Brazilian energy mix.

4.3.2.5.4 INVENTORY OF GLASS RECYCLING

Data about the consumption of energy, water and other materials related to sorting and crushing of glass to obtain glass cullets were obtained from the process “Glass cullet, sorted {RoW}| treatment of waste glass from unsorted public collection, sorting | Alloc Def, U” of Ecoinvent v.3.1 (2014) database updated with Brazilian energy mix.

4.3.2.6 ENVIRONMENTAL CREDITS ASSOCIATED WITH MINERAL FRACTION RECYCLING

Recovered materials obtained from mineral fraction recycling are used in substitution of the primary materials listed in Table 39. The Brazilian Standard NBR 15.115 (ABNT, 2004a) establishes the procedures for the use of C&DW recycled aggregates in pavement layers, allowing its use as material for base, subbase and subgrade reinforcement of roads. In particular, the use as base material is only permitted for low-traffic roads, with a daily traffic lesser than 400 vehicles (KELLER; SHERAR, 2003; ABNT, 2004a; LEITE *et al*., 2011). Then, it was assumed that fine RA, coarse RA type A and B and, excavated soil correspond to the equivalent type of natural raw material that would be employed for the same end-use.

Table 39. Substitute materials obtained from mineral fraction recycling.

Recovered material	**Substitute material**	**LCI of substitute material production**
Excavated soil	Soil[1]	Ecoinvent v. 3.1 (2014)
Fine RA (0.15 to 4.75 mm)	Sand and gravel[2]	Ecoinvent v. 3.1 (2014)
Coarse RA Type A (4.75 to 25 mm)	Natural aggregate (4.75 to 25 mm)	Rosado *et al*. (2017)
Coarse RA Type B (0.1 to 50 mm)	Natural aggregate (0.1 to 50 mm)	Rosado *et al*. (2017)

Notes: [1]Process "Clay {RoW}| clay pit operation | Alloc Def, U" of Ecoinvent v.3.1 (2014) database updated with Brazilian energy mix. [2]Process "Sand {RoW}| gravel and quarry operation | Alloc Def, U" of Ecoinvent v.3.1 (2014) database updated with Brazilian energy mix.

Table 40 lists the direct burdens of the primary materials production. Data about soil extraction, sand and gravel were obtained from Ecoinvent v.3.1 (2014) database and data about natural aggregate production were obtained from Rosado *et al*. (2017).

Table 40. Inputs from background system for soil, sand and gravel, and natural aggregates production.

Consumptions for the production of 1 t	**Soil**	**Sand and gravel**	**Natural aggregate (4.75 to 25 mm)**	**Natural aggregate (0.1 to 50 mm)**
Soil, in ground (t)	1.00	-	-	-
Gravel, in ground (t)	-	1.04	-	-
Basalt, mineral (t)	-	-	1.05	1.05
Explosive (g)	-	-	145	145
Electricity (kWh)	-	2.72	3.67	1.00
Diesel (MJ)	29.70	14.70	7.67	7.67
Lubricating oil (kg)	-	0.002	0.002	0.002
Water (L)	-	1390	8.10	8.10
Handling (tkm)	-	-	1.00	1.00
Landfilling (t)	-	0.003	-	-

4.3.2.7 ENVIRONMENTAL CREDITS ASSOCIATED WITH NON-MINERAL FRACTION RECYCLING

Table 41 lists the substitute materials obtained from the non-mineral fraction recycling and the substitution ratio used to estimate the environmental credits associated with the recovered materials. The environmental credits of the recovered materials obtained from steel and glass recycling have been calculated based on the approach proposed by Gala *et al*. (2015), taking into account the current proportion of recycled and virgin material in the average market mix. The inventory data of all substitute material production were obtained from Ecoinvent v.3.1 (2014).

Table 41. Substitute material obtained from non-mineral fraction recycling and the susbtitution ratio used in this study.

Recovered material	**Substitute material**	**Source[1]**	**Substitution ratio**	**Source**
Recycled wood chips	Wood chips	Primary data	1:1	Primary data
Recycled steel	Primary (60%) and secondary (40%) steel	Vitale *et al*. (2017) and WSA (2011)	1:0.98	Vitale *et al*. (2017) and WSA (2011)
Recycled granules of PVC	Primary granules of PVC	Brazilian PVC Institute (2017)	1:0.81	Rigamonti *et al*.(2009)
Recycled granules of HDPE	Primary granules of HDPE	Abiplast (2017)	1:0.81	Rigamonti *et al*. (2009)
Recycled granules of PET	Primary granules of PET	Abiplast (2017)	1:0.81	Rigamonti *et al*. (2009)
Recycled granules of PP	Primary granules of PP	Abiplast (2017)	1:0.81	Rigamonti *et al*. (2009)
Glass cullet	Primary (55%) and secondary (45%) glass	Cempre (2011)	1:0.82	Cremiato *et al*. (2017)

Note: [1]Source used to determine the substitute materials.

4.3.2.7.1 RECYCLED WOOD CHIPS

The recycled wood chips have similar caracteristics in relation to the wood chips obtained from firewood grinding (Table 42). In Brazil, the wood chips used in the industries as biomass are obtained from eucalyptus (83%), pinus (9%) and other wood species (8%) (ABRAF, 2013). Then, it was assumed that the recycled wood chips substitute the wood chips made from eucalyptus, which is classified as hardwood. Direct and indirect environmental burdens of wood chips production were obtained from the process “Residual wood, dry {GLO}| shaving, hardwood, measured as dry mass to generic market for residual wood, dry | Alloc Def, U” of Ecoinvent v.3.1 (2014) database.

Table 42. Caracteristics of wood materials used as biomass.

Wood materials	Moisture (%)	Calorific Value (kcal/kg)	Density (kg/m³)	Note
Sawing chips	45	2200	380	Containing up to 30% sawdust.
Sawdust	45	2200	380	
Wood chips	35	2900	280	From eucalyptus and pinus grinding.
Recycled wood chips	22	3200	250	Free from metals and other impurities.

Note: [1]Data from Schürhaus (2007) and Opção Verde Biomass Industry (2017).

4.3.2.7.2 RECYCLED STEEL

Steel recycling accounts for significant energy and raw material savings. According to the World Steel Association (2018), over 1.4 t of iron ore, 0.74 t of coal, and 0.12 t of limestone are saved for every 1 t of steel scrap made into new steel. LCA studies have been adopting different approaches to calculate the environmetal credits of recycled steel. Houssain, Wo and Poon (2017) assumed that the reycled steel avoids the iron ore extraction, while Mercante *et al.* (2012) and Turk *et al.* (2015) assumed that it avoids the pig iron production, and Rigamonti, Grosso and Sunseri (2009) assumed that it avoids the liquid iron production.

Vitale *et al*. (2017) assumed that the recycled steel replaces the average mix of virgin and recycled materials utilised by the market, that represent 60% of primary steel (produced by BOF process) and 40% of secondary steel (produced by EAF process), based on data from World Steel Association report (WSA, 2011) and using the approach proposed by Gala *et al*. (2015). Then, considering that globally, about 70% of steel is produced using the BOF process, 29% is produced via the EAF process and 1% using the open hearth furnace (WSA, 2011), the assumption of Vitale *et al*. (2017) appears as the most adequate, and was adopted in this study. The direct and indirect burdens of primary steel production were obtained from the process “Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Def, U” of Ecoinvent v.3.1 (2014), updated with Brazilian energy mix.

4.3.2.7.3 RECYCLED PLASTICS

Granules of recycled plastics are used in the industry to replace their respective virgin resins. However, due to changes in their properties, it is not appropriate to consider that 1 ton of granules of recycled plastic replaces 1 ton of virgin resin. In this context, LCA studies related to C&DW management have been adopting the substitution ratio of 1:0.81, which means that 1 ton of granules of recycled plastic replaces 0.81 ton of virgin resin (MERCANTE *et al*., 2012; HOSSAIN; WO; POON, 2017). Originally this factor was defined by Rigamonti, Grosso and Sunseri (2009), based on the Italian market price of granules of recycled plastic in relation to virgin resin. Considering the absence of data, in this study, the substitution factor of 1:0.81 was used.

The direct and indirect burdens related to the primary plastics production were obtained from the processes of Ecoinvent v.3.1 (2014): “Polyethylene, high density, granulate {RoW}| production | Alloc Def, U”; “Polyethylene terephthalate, granulate, amorphous {RoW}| production | Alloc Def, U”; “Polypropylene, granulate {RoW}| production | Alloc Def, U"; "Polyvinylchloride, suspension polymerised {RoW}| polyvinylchloride production, suspension polymerisation | Alloc Def, U".

4.3.2.7.4 RECYCLED GLASS

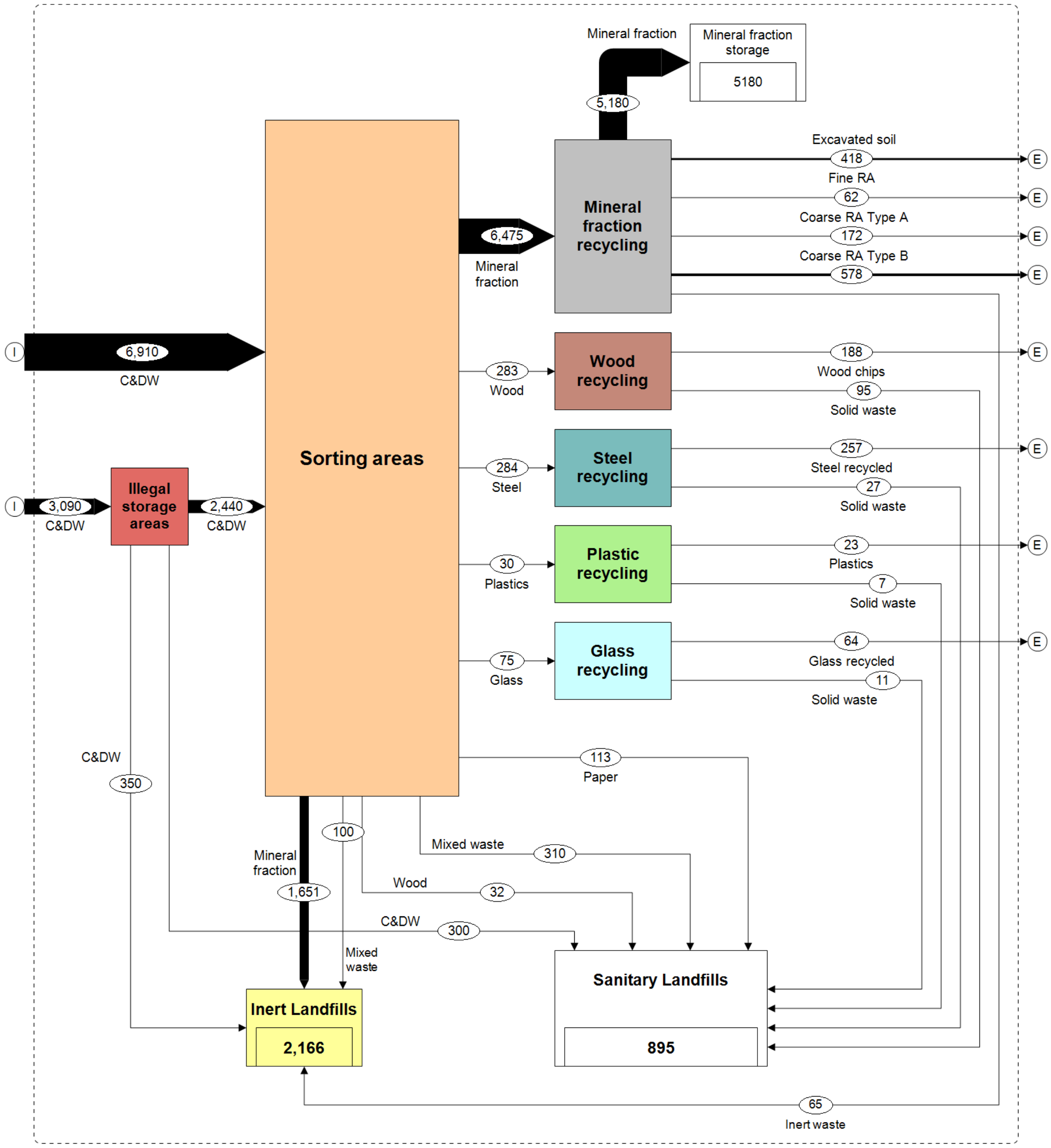
Recycled glass (cullets) are sent to production of glass packaging. It is estimated that the packaging sector uses 45% of cullets (CEMPRE, 2011). In this context, it was considered that the recycled glass susbtitutes 55% of primary glass and 45% of secondary glass. The substitution ratio of 1:0.82 adopted was obtained from the study of Cremiato *et al*. (2017).

4.3.2.8. SUMMARY OF THE BASE LIFE CYCLE INVENTORY

Figure 57 describes the C&DW management system related to the base case scenario, as quantified by a material flow analysis, and taking into account all the assumptions adopted in the phase of goal and scope definition and the inventory data. There is a significant amount of mineral fraction that remain stored in the recycling facilities (5,180 tonnes), and in this case, only the environmental burdens related to its transport from sorting areas to recycling facilities have been considered in the LCI.

Table 43 summarizes the transport phases, which are related to the system boundaries (see Figure 46), and Tables 44, 45 and 46 report the main environmental burdens, direct and avoided, related to the base case scenario considering the management of 10,000 t of C&DW per year.

Figure 57. Material flow analysis of C&DW management system related to the base case scenario, with the indication of the main input (I) and exit (E). Data are expressed in tonnes.



Source: Rosado *et al*. (2019).

Table 43. Transport phases related to 10,000 tons of C&DW management, in the base case scenario.

Transport	**Quantity (t)**	**Distance (km)**	**Transport unit (tkm)**
C&DW from generator to illegal storage areas (tu_1)	3,090	90	23,820
C&DW from generator to sorting areas (tu_2)	6,910	90	47,980
C&DW from illegal storage areas to sorting areas (tu_3)	2,440	69	31,320
C&DW from illegal storage areas to landfill (tu_4)	650	86	8,220
Mineral fraction from sorting areas to landfill (tu_5)	1,651	68	18,836
Wood from sorting areas to landfill (tu_5)	32	69	517
Paperboard from sorting areas to landfill (tu_5)	113	358	3,132
Mixed waste from sorting areas to landfill (tu_5)	409	358	11,344
Mineral fraction from sorting areas to recycling (tu_6)	6,475	48	72,524
Wood from sorting areas to recycling (tu_6)	283	274	21,542
Steel from sorting areas to recycling (tu_6)	284	1,058	25,448
Plastics from sorting areas to recycling (tu_6)	30	612	1,233
Glass from sorting areas to recycling (tu_6)	74	1,303	8,248

Table 44. Main direct burdens related to the collection, sorting and landfilling of 10,000 t of C&DW management, in the base case scenario.

Consumptions	
C&DW collection from illegal storage areas	
Diesel (MJ)	31,320
Lubricating oil (kg)	14.40
C&DW sorting	
Diesel (MJ)	22,680
Lubricating oil (kg)	10.42
Air emissions	
Carbon dioxide, fossil (kg)	4,051.50
Nitrogen oxides (kg)	79.22
Carbon monoxide, fossil (kg)	21.04
Particulates, > 2.5µm, and < 10µm (kg)	2.48
VOC, volatile organic compounds (kg)	2.03
Sulfur oxides (kg)	0.90
Methane, fossil (kg)	0.20
Dinitrogen monoxide (kg)	0.10
Propene (kg)	0.06
Formaldehyde (kg)	0.03
Benzene (kg)	0.02
Acetaldehyde (kg)	0.02
Toluene (kg)	0.01
Xylene (kg)	0.01
PAH, polycyclic aromatic hydrocarbons (kg)	0.004
Acrolein (kg)	0.002
Butadiene (kg)	0.001
Landfilling	
C&DW from illegal storage areas inert landfilling (t)	350
C&DW from illegal storage areas sanitary landfilling (t)	300
Mineral fraction from sorting areas inert landfilling (t)	1,651
Wood from sorting areas sanitary landfilling (t)	32
Paperboard from sorting areas sanitary landfilling (t)	113
Mixed waste from sorting areas sanitary landfilling (t)	310
Mixed waste from sorting areas inert landfilling (t)	100

Table 45. Main direct burdens related to the C&DW recycling, in the base case scenario (Part I).

Consumptions	
Mineral fraction recycling	
Diesel (MJ)	23,588
Lubricating oil (kg)	7.55
Electricity (kWh)	18,434
Water (m³)	1.44
Wood recycling	
Diesel (MJ)	25,266
Lubricating oil (kg)	11
Electricity (kWh)	2,312
Steel recycling	
Iron scrap, sorted (kg)	283,956
Electricity (kWh)	146,387
Quicklime (kg)	13,410
Oxygen, liquid (kg)	13,117
Natural gas (m³)	6,476
Hard coal (kg)	3,598
Water (m³)	1,325
Ferrosilicon (kg)	951
Diesel (MJ)	889
Argon, liquid (kg)	846
Propane (MJ)	702
Plastics recycling	
Diesel (MJ)	367
Electricity (kWh)	39,991
Water (m³)	23.68
Sodium hydroxide (kg)	6
Glass recycling	
Water (m³)	15.81
Electricity (kWh)	235.62
Air emissions	
Carbon dioxide, fossil (kg)	3,692.27
Carbon monoxide, fossil (kg)	619.67
Nitrogen oxides (kg)	119.91
Ammonia (g)	49.80
Particulates, > 2.5 µm, and < 10µm (kg)	46.89
Particulates, < 2.5 µm (kg)	42.25
Hydrocarbons, aromatic (kg)	19.79
Sulfur dioxide (kg)	19.79
Particulates, > 10 µm (kg)	15.05
Zinc (kg)	5.85
NMVOC, non-methane volatile organic compounds, unspecified origin (kg)	3.75
VOC, volatile organic compounds (kg)	1.85
Sulfur oxides (kg)	1.42
Hydrogen chloride (kg)	1.34
Xylene (kg)	1.06
Benzene (kg)	0.61
Hydrogen fluoride (kg)	0.60
Mercury (kg)	0.58
Lead (kg)	0.46
Chromium (kg)	0.32
Methane, fossil (kg)	0.18
Nickel (kg)	0.18

Table 45. Main direct burdens related to the C&DW recycling, in the base case scenario (Part II).

Air emissions	
Dinitrogen monoxide (kg)	0.09
Copper (kg)	0.06
Propene (kg)	0.06
Acetaldehyde (kg)	0.02
Formaldehyde (kg)	0.02
PAH, polycyclic aromatic hydrocarbons (kg)	0.01
Benzene, hexachloro- (kg)	0.01
Cadmium (kg)	0.01
Polychlorinated biphenyls (kg)	0.01
Toluene (kg)	0.01
Acrolein (kg)	0.002
Butadiene (kg)	0.001
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p- (kg)	1.17E-06
Emissions to water	
Suspended solids, unspecified (g)	228
BOD5, Biological Oxygen Demand (g)	185
COD, Chemical Oxygen Demand (g)	1,614
Oils, unspecified (g)	39
Ammonia (g)	50
Landfilling	
Inert residues (t)	65
Wood residues (t)	95
Steel process losses (t)	27
Plastic residues (t)	7
Glass residues (t)	11

Table 46. Avoided burdens related to 10,000 tons of C&DW management, in the base case scenario.

Avoided burdens	**Quantity (t)**
Soil	418
Natural aggregates	812
Wood chips	188
Primary steel	154
Secondary steel	103
Granules of PVC	10
Granules of HDPE	5
Granules of PET	2
Granules of PP	1
Primary glass	29
Secondary glass	24

CHAPTER

5

RESULTS AND DISCUSSION

This chapter presents the “Life Cycle Impact Asssessment” and “Interpretation” stages. In addition, it comprises the discussion of the results and some recommendations of potential improvements on the management system of the C&DW from small generators.

5.1 RESULTS OBTAINED BY CML BASELINE V3.03

Table 47 presents the characterised and normalised results obtained by using the CML baseline v3.03 methodology, and the contributions of each impact category with reference to the total impact after normalisation. According to Zampori *et al.* (2016), the identification of the significant impact categories shall be based on the normalised and/or weighted results of the study, thence, “Marine Aquatic Ecotoxicity” is the most important impact category, accounting for almost 90% of the total impacts.

Table 47. Environmental profile of C&DW management system related to the functional unit, in the base case scenario. Data obtained by CML baseline.

Impact category	Characterisation		Normalisation (World)	Contribution (based on normalisation)
Marine aquatic ecotoxicity	**-6.79E+07**	**kg 1,4-DB eq**	**-3.50E-07**	**89.70%**
Human toxicity	-3.30E+04	kg 1,4-DB eq	-1.28E-08	3.27%
Terrestrial ecotoxicity	1.13E+04	kg 1,4-DB eq	1.03E-08	2.64%
Abiotic depletion (fossil fuels)	-2.00E+06	MJ	-5.25E-09	1.34%
Acidification	-8.55E+02	kg SO_2 eq	-3.58E-09	0.92%
Photochemical oxidation	-1.14E+02	kg C_2H_4 eq	-3.10E-09	0.79%
Global warming	-9.71E+04	kg CO_2 eq	-2.32E-09	0.59%
Abiotic depletion	3.03E-01	kg Sb eq	1.45E-09	0.37%
Fresh water aquatic ecotox.	2.65E+03	kg 1,4-DB eq	1.12E-09	0.29%
Eutrophication	4.47E+01	kg PO_4^{3-} eq	2.83E-10	0.07%
Ozone layer depletion	2.16E-03	kg CFC-11 eq	9.54E-12	0.00%

Figure 58 shows the processes contribution of each stage of the C&DW management system, based on the characterised inventory results. C&DW management stages have been grouped in order to simplify the analysis. In the legend of the following graphs, **transport** includes all transport phases (see Figure 46 and Table 43); **C&DW collection** refers to C&DW disposed in illegal storage areas (see Table 26); **C&DW sorting** comprises all sorting operations detailed in section 4.3.2.3; **C&DW landfilling** includes the final disposal of mineral fraction, wood, paperboard and mixed wastes, as reported in Tables 22 and 23; and **recycling** items are related to the recycling processes, as described in the sections 4.3.2.4 and 4.3.2.6 for mineral fraction and sections 4.3.2.5 and 4.3.2.7 for non-mineral fraction.

Figure 58. Environmental impact contribution of the main stages related to C&DW management system in the base case scenario (in percentages of the total impact). Data obtained by CML baseline.

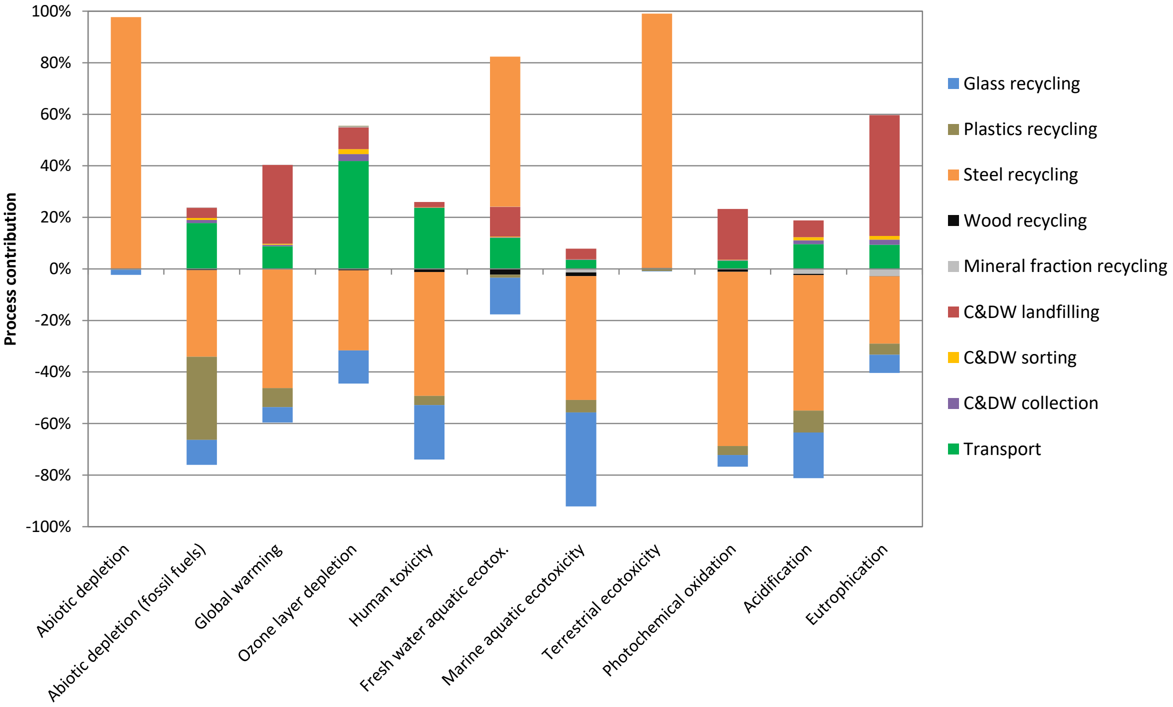


Table 48 presents the contribution of the stages for each impact category. The values in bold represent the most significant stages that together contribute over 80% to a specific impact category. The highlighted values represent the avoided impacts showed in Figure 58.

The avoided impacts of steel recycling are important for most impact categories, with the exception of that of “Abiotic Depletion”, “Fresh Water Aquatic Ecotoxicity” and “Terrestrial Ecotoxicity”.

Considering that the production of recycled aggregates avoids the natural resources extraction, it was expected avoided impacts for “Abiotic Depletion”, but the mineral fraction recycling avoids less than 1% of the impacts of this category. Although “Abiotic Depletion” comprises the environmental impacts of resource use, it does not consider the extraction of soil, sand and gravel used for the production of natural aggregates as an important contributer for the impacts. This fact can be justified by the availability of quarries and readiness extraction of these raw materials.

In fact, in the CML baseline method the majority of the impacts of “Abiotic Depletion” are related to the scarcity of silver (61%), lead (18%), zinc (14%) and copper (7%) (BENINI *et al*., 2014). The abiotic depletion factor is determined for each mineral based on its reserves at a global scale (EC-JRC, 2011).

Transport and C&DW landfilling are the main responsible for the generated impacts of almost all impact categories. Transport mainly influences “Ozone Layer Depletion” (42%), Human Toxicity (24%) and “Abiotic Depletion (fossil fuels)” (18%), while C&DW landfilling mainly influences “Eutrophication” (47%), “Global Warming” (31%) and “Photochemical Oxidation” (20%).

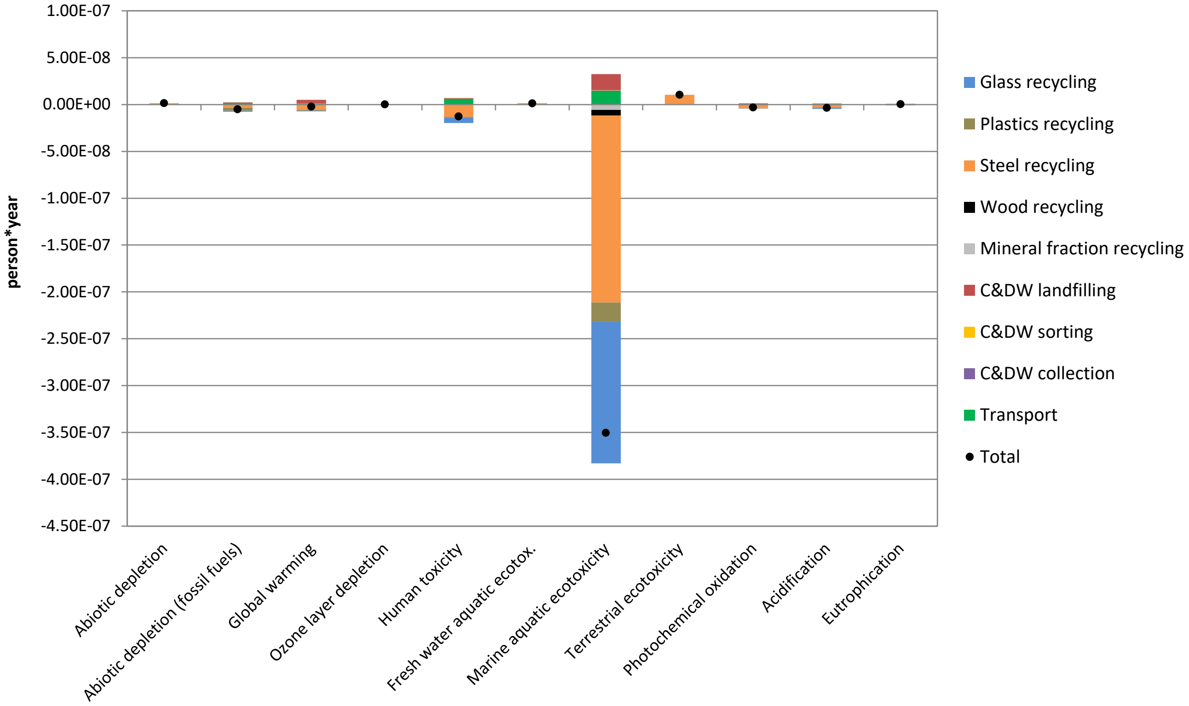
Glass and plastics recycling contributes for the avoided impacts of most impact categories. Glass recycling mainly contributes to “Marine Aquatic Ecotoxicity” (36%) and plastics recycling to “Abiotic Depletion (fossil fuels)” (32%). Otherwise, mineral fraction and wood recycling have minor contribution for the avoided impacts.

Table 48. Contribution percentage of the main stages related to C&DW management system in the base case scenario. The values in bold represent the most significant stages that together contribute over 80% to a specific impact category and the values highlighted in grey indicate avoided impacts. Data obtained by CML baseline.

Impact category	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling	Total
Abiotic depletion	0.11%	0.00%	0.00%	0.03%	0.03%	0.03%	**97.51%**	0.28%	1.99%	**97.51%**
Abiotic depletion (fossil fuels)	**17.81%**	1.14%	0.83%	3.99%	0.16%	0.47%	**33.58%**	**32.31%**	9.70%	**83.71%**
Global warming	**8.81%**	0.55%	0.39%	**30.60%**	0.08%	0.25%	**46.00%**	7.42%	5.91%	**85.40%**
Ozone layer depletion	**41.83%**	2.70%	1.95%	8.41%	0.37%	0.60%	**31.01%**	0.24%	**12.89%**	**85.72%**
Human toxicity	**23.65%**	0.18%	0.13%	2.04%	0.16%	1.00%	**48.11%**	3.58%	**21.14%**	**92.90%**
Fresh water aquatic ecotoxicity	**12.06%**	0.27%	0.19%	11.52%	0.08%	2.26%	**58.25%**	1.19%	**14.19%**	**84.49%**
Marine aquatic ecotoxicity	3.52%	0.11%	0.08%	4.12%	1.35%	1.42%	**48.10%**	4.84%	**36.47%**	**84.57%**
Terrestrial ecotoxicity	0.34%	0.00%	0.00%	0.11%	0.00%	0.12%	**98.56%**	0.66%	0.21%	**98.56%**
Photochemical oxidation	3.15%	0.24%	0.17%	**19.68%**	0.01%	1.12%	**67.57%**	3.50%	4.56%	**87.25%**
Acidification	**9.59%**	1.55%	1.12%	6.57%	1.89%	0.49%	**52.59%**	**8.50%**	**17.70%**	**88.39%**
Eutrophication	**9.35%**	1.98%	1.44%	**46.90%**	2.80%	0.07%	**26.15%**	4.25%	7.06%	**82.39%**

Figure 59 shows the normalised results in terms of person*year units, which represents the global average impact in a specific category associated with one person during one year (considering the world in the year 2000 as reference). As highlighted in Table 48, “Marine Aquatic Ecotoxicity” appears as the most important category. Normalised results confirm the importance of steel and glass recycling for the avoided impacts. The same observations can be applied for the normalised results acquired by using the normalisation factors with reference to Europe (Figure A4.1 – Appendix 4).

Figure 59. Normalised results of impact assessment related to the C&DW management system in the base case scenario, obtained by using normalised factors for World (2000) of CML baseline methodology.

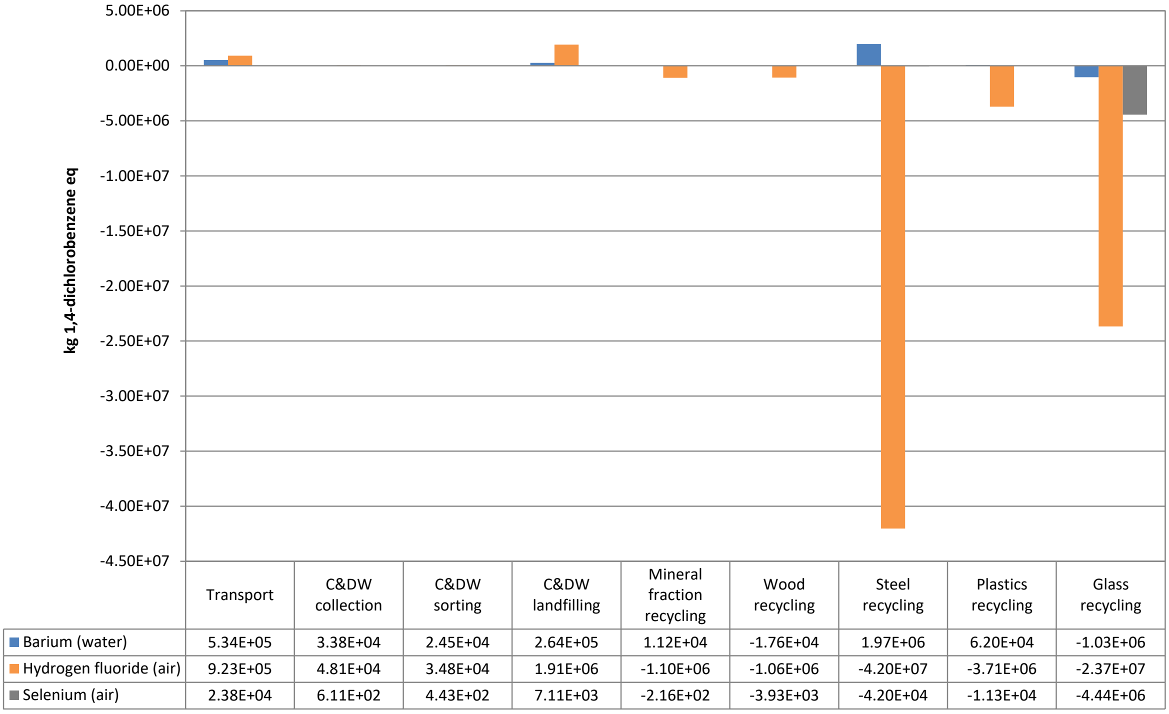


The contribution analysis for “Marine Aquatic Ecotoxicity” category (Figure 60) shows that the avoided impacts of steel and glass recycling are related to air emissions of hydrogen fluoride from iron pellet production and primary glass production, respectively.

It is important to develop a critical assessment about the reliability of the above reported results, since the various characterisation models can have different degree of uncertainty. The comparison with the results obtained by other LCIA methodologies is a possible approach to develop this assessment and verify if these results can be considered as sufficiently reliable.

Taking into account the ILCD recommendations, there are no methodologies recommended for the assessment of “Marine Aquatic Ecotoxicity”, since none of them is developed enough. Amongst the four ecotoxicity methodologies currently recommended (USEtox, Impact 2002+, ReCiPe and TRACI), only USEtox midpoint model appears sufficiently developed and only for "Fresh Water Aquatic Ecotoxicity" impacts (EC-JRC, 2011). For this reason, it is not appropriate taking into account "Marine Aquatic Ecotoxicity", "Fresh Water Aquatic Ecotoxicity" and "Terrestrial Ecotoxicity" categories. Table 49 and Figure 61 processed the previous results based on this conclusion.

Figure 60. Contribution analysis for the impact category "Marine Aquatic Ecotoxicity" for the C&DW management system in the base case scenario.



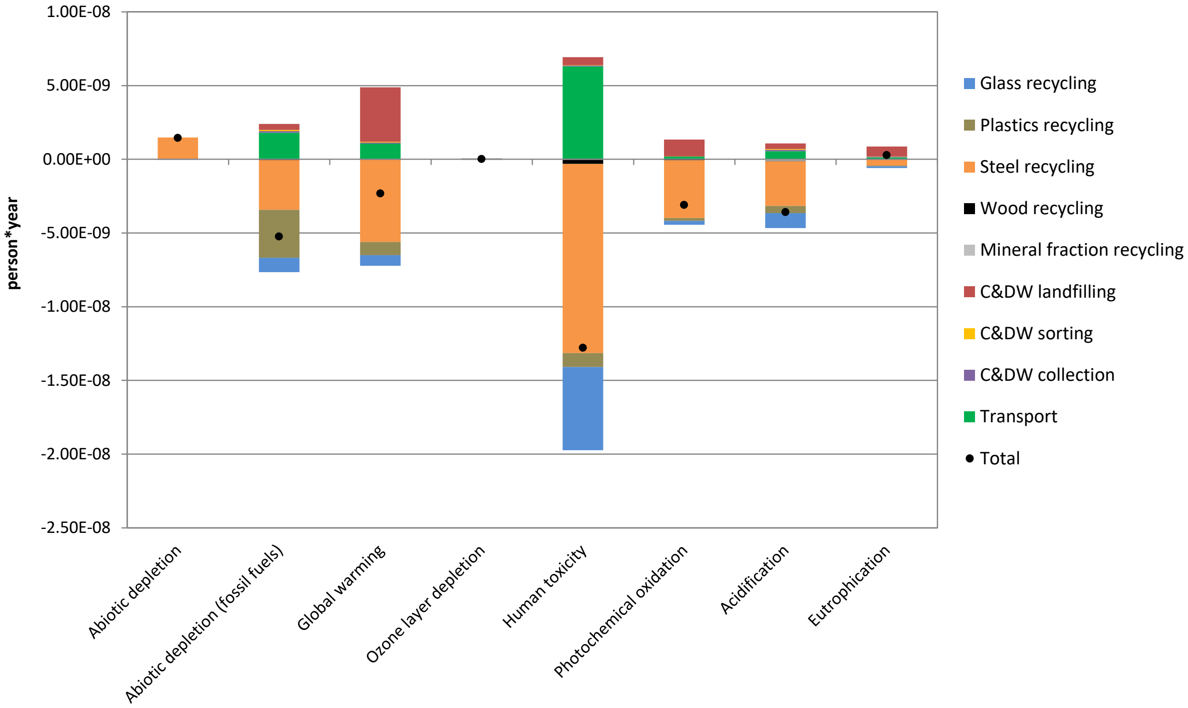
	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
🟦 Barium (water)	5.34E+05	3.38E+04	2.45E+04	2.64E+05	1.12E+04	-1.76E+04	1.97E+06	6.20E+04	-1.03E+06
🟧 Hydrogen fluoride (air)	9.23E+05	4.81E+04	3.48E+04	1.91E+06	-1.10E+06	-1.06E+06	-4.20E+07	-3.71E+06	-2.37E+07
⬛ Selenium (air)	2.38E+04	6.11E+02	4.43E+02	7.11E+03	-2.16E+02	-3.93E+03	-4.20E+04	-1.13E+04	-4.44E+06

Then, the new results show "Human Toxicity" as the most important category, accounting for 44% of the total impacts. Five impact categories, reported in bold in Table 49, were selected as significant for this study, since they account for 94% of the total impacts.

Table 49. Environmental profile of C&DW management system related to the functional unit, in the base case scenario. Excluding “Marine Aquatic Ecotoxicity”, “Fresh Water Aquatic Ecotoxicity” and “Terrestrial Ecotoxicity” categories. Data obtained by CML baseline.

Impact category	**Characterisation**		**Normalisation (World)**	**Contribution (based on normalisation)**
Human toxicity	**-3.30E+04**	**kg 1,4-DB eq**	**-1.28E-08**	**44.45%**
Abiotic depletion (fossil fuels)	**-2.00E+06**	**MJ**	**-5.25E-09**	**18.23%**
Acidification	**-8.55E+02**	**kg SO$_2$ eq**	**-3.58E-09**	**12.44%**
Photochemical oxidation	**-1.14E+02**	**kg PO$_4^{3-}$ eq**	**-3.10E-09**	**10.76%**
Global warming	**-9.71E+04**	**kg CO$_2$ eq**	**-2.32E-09**	**8.06%**
Abiotic depletion	3.03E-01	kg Sb eq	1.45E-09	5.03%
Eutrophication	4.47E+01	kg PO$_4^{3-}$ eq	2.83E-10	0.98%
Ozone layer depletion	2.16E-03	kg CFC-11 eq	9.54E-12	0.03%

Figure 61. Normalised results of impact assessment related to the C&DW management system in the base case scenario, obtained by using normalised factors for World (2000) of CML baseline methodology. Excluding “Marine Aquatic Ecotoxicity”, “Fresh Water Aquatic Ecotoxicity” and “Terrestrial Ecotoxicity” categories.



The contribution analysis for the categories highlighted in Table 49 are available in Appendix A (Figures A4.2 to A4.6), and Table 50 supports the analysis of data obtained from the contribution analysis. “Abiotic Depletion”, “Eutrophication” and “Ozone Layer Depletion” were not included in the contribution analysis due to negligible contribution for the total impacts.

After exclusion of “Marine Aquatic Ecotoxicity”, “Fresh Water Aquatic Ecotoxicity” and “Terrestrial Ecotoxicity”, the normalised results still confirm the importance of steel recycling for the avoided impacts, followed by glass recycling.

The environmental benefits of steel recycling result from the avoided consumptions of coal for “Abiotic Depletion (fossil fuels)”, pig iron for “Global Warming”, coke for “Human Toxicity”, and sinter iron for “Photochemical Oxidation” and “Acidification”, which are used in the primary steel production.

The contribution of glass recycling for “Human Toxicity” and “Acidification” is related to the avoided emissions of selenium and sulphur dioxides, both from the primary glass production.

The recovery of PVC and HDPE are the main responsible for the environmental benefits of plastics recycling. For “Abiotic Depletion (fossil fuels)”, it is related to the avoided consumption of crude oil and natural gas, and for “Acidification” due to the avoided emission of sulphur dioxide from primary plastics production.

The transport stages are responsible for the consumption of 76% of the total crude oil used throughout the C&DW management system, which justifies its contribution for “Abiotic Depletion (fossil fuel)”. C&DW freights from generator to sorting areas and those for mineral fraction from sorting areas to recycling facilities appear as the main stages responsible for the air emissions of carbon dioxide (for “Global Warming”) and nitrogen oxides (for “Acidification”). The contribution for “Human Toxicity” is related to air emissions of antimony from brake wear of trucks.

The impacts of C&DW landfilling are important for “Global Warming” and “Photochemical Oxidation”, due to emissions of biogenic methane related to paperboard waste landfilling.

Table 50. Main data obtained from contribution analysis of life cycle impact assessment results acquired by CML baseline.

Impact categories	Important stages	Important elementary flows	Important processes
Human toxicity	Steel recycling (-)	Benzene	Coke production
	Glass recycling (-)	Selenium	Primary glass production (without cullets)
	Transport (+)	Antimony	Brake wear emissions (lorry)
Abiotic depletion (fossil fuels)	Steel recycling (-)	Hard coal	Hard coal mine operation
	Plastics recycling (-)	Crude oil Natural gas	PVC suspension polymerised and HDPE granulate production
	Transport (+)	Crude oil	Petroleum production
Acidification	Steel recycling (-)	Sulphur dioxide	Sinter iron production
	Glass recycling (-)	Sulphur dioxide	Primary glass production (without cullets)
	Plastics recycling (-)	Sulphur dioxide	PVC suspension polymerised and HDPE granulate production
	Transport (+)	Nitrogen oxides	Transport, lorry 16-32 metric ton (EURO4)
		Sulphur dioxide	Petroleum refinery operation
Photochemical oxidation	Steel recycling (-)	Carbon monoxide (fossil)	Sinter iron production
	C&DW landfilling (+)	Methane (biogenic)	Paperboard waste landfilling
Global warming	Steel recycling (-)	Carbon dioxide (fossil)	Pig iron production
	C&DW landfilling (+)	Methane (biogenic)	Paperboard waste landfilling
	Transport (+)	Carbon dioxide (fossil)	Transport, lorry 16-32 metric ton (EURO4)

Legend

(+) Environmental impact (-) Avoided environmental impact

🟦 Emission into air 🟧 Emission into soil 🟩 Emission into water 🟨 Raw material

5.2 RESULTS OBTAINED BY IMPACT 2002+ V2.12

Table 51 lists the characterised and normalised results obtained by Impact 2002+. As already highlighted, normalisation factors for Brazil or World are not available for this methodology. Nevertheless, the normalised results were analysed considering that no difference was observed by comparing World normalised factors with European ones using CML baseline methodology (see Figure A4.1 – Appendix 4), except for the magnitude of the values (normalised impacts for Europe presented highest values). Five impact categories, reported in bold in Table 51, appeared significant, accounting for 95% of the total impacts.

Table 51. Environmental profile of C&DW management system related to the functional unit, in the base case scenario. Data obtained by Impact 2002+.

Impact category	Characterisation		Normalisation (Europe)	Contribution (based on normalisation)
Respiratory inorganics	**-2.36E+02**	**kg $PM_{2.5}$ eq**	**-2.33E+01**	**27.65%**
Global warming	**-2.06E+05**	**kg CO_2 eq**	**-2.08E+01**	**24.70%**
Carcinogens	**4.02E+04**	**kg C_2H_3Cl eq**	**1.59E+01**	**18.84%**
Non-renewable energy	**-2.16E+06**	**MJ primary**	**-1.42E+01**	**16.87%**
Non-carcinogens	**1.57E+04**	**kg C_2H_3Cl eq**	**6.19E+00**	**7.35%**
Terrestrial ecotoxicity	4.50E+06	kg TEG soil	2.60E+00	3.08%
Land occupation	-8.12E+03	m^2org.arable	-6.46E-01	0.77%
Mineral extraction	-5.81E+04	MJ surplus	-3.83E-01	0.45%
Terrestrial acid/nutri	-2.09E+03	kg SO_2 eq	-1.59E-01	0.19%
Respiratory organics	-2.33E+02	kg C_2H_4 eq	-7.00E-02	0.08%
Ionizing radiation	3.45E+05	Bq C-14 eq	1.02E-02	0.01%
Aquatic ecotoxicity	-2.78E+06	kg TEG water	-1.02E-02	0.01%
Ozone layer depletion	2.16E-03	kg CFC-11 eq	3.20E-04	0.0004%
Aquatic acidification	-3.44E+02	kg SO_2 eq	0.00E+00	-
Aquatic eutrophication	-8.24E+00	kg PO_4 P-lim	0.00E+00	-

The results obtained by Impact 2002+ are reported in Figure 62 and with more detail in Table 59. Steel recycling is the stage that gives the most important contribution for the higher number of impact categories, namely in terms of avoided impacts. However, the process contributes significantly to generated impacts of the two human toxicity categories (86% for “Carcinogens” and 76% for “Non-Carcinogens”). C&DW transport and landfilling stages also appear crucial, with the first which provides the largest contribution to “Aquatic and Terrestrial Ecotoxicities” and, above all, to “Ionizing Radiation” and “Ozone Layer Depletion”. On the other hand, C&DW collection and sorting stages determine only nugatory impact.

It appears remarkable the contribution of wood recycling for “Land Occupation” (70%), and the contribution of mineral fraction recycling for “Aquatic Ecotoxicity” (19%) and “Terrestrial Ecotoxicity” (19%) categories. The relative importance of all these contributions is better showed by the normalised results in Figure 63. They indicate that five impact categories, namely “Carcinogens”, “Non-Carcinogens”, “Respiratory Inorganics”, “Global Warming” and “Non-Renewable Energy” have a major role and must be carefully monitored. For all these categories, the key stages are always steel recycling, plastics recycling, glass recycling, transport and landfilling.

It is important to highligh the negligible importance of the avoided impacts of recycled aggregates for the results of “Mineral Extraction”. This category considers that the extraction of a specific amount of mineral resource leads to an additional energy requirement for future mining of this resource (JOLLIET *et al*., 2003). Despite the difference in comparison with the “Abiotic Depletion” category of CML *baseline*, the results are similar, since extraction of metals (as nickel and copper) appears as the most important for the impacts of “Mineral Extraction” category.

Figure 62. Environmental impact contribution of the main stages related to C&DW management system in the base case scenario (in percentages of the total impact). Data obtained by Impact 2002+.

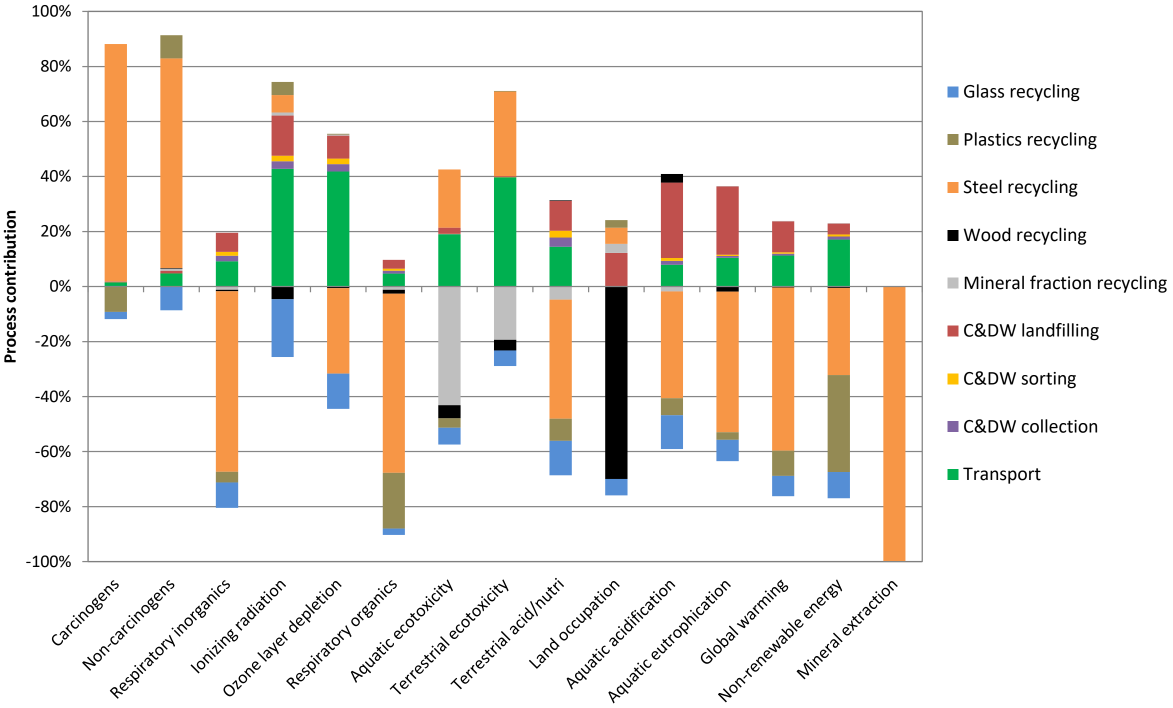
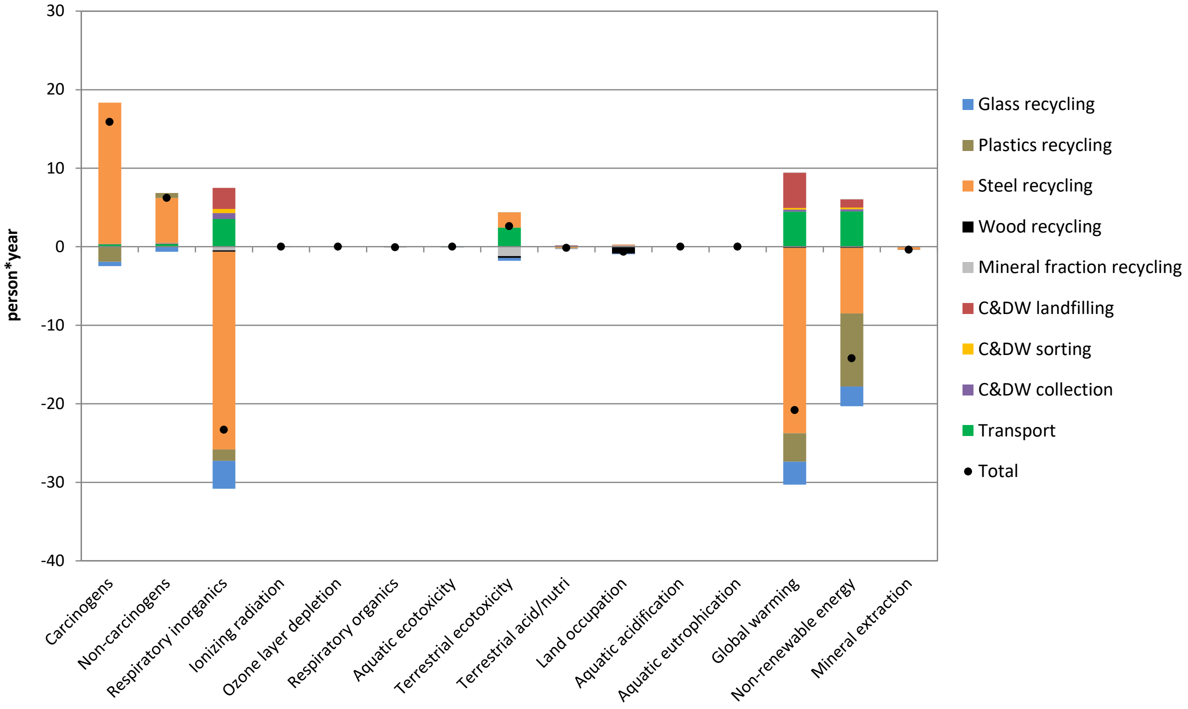


Table 52. Contribution percentage of the main stages related to C&DW management system in the base case scenario. The values in bold represent the most significant stages that together contribute over 80% to a specific impact category and the values highlighted in grey indicate avoided impacts. Data obtained by Impact 2002+.

Impact category	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling	Total
Carcinogens	1.54%	0.03%	0.02%	0.19%	0.06%	0.03%	**86.32%**	**9.21%**	2.59%	**95.53%**
Non-carcinogens	4.76%	0.02%	0.02%	0.93%	0.80%	0.20%	**76.19%**	**8.43%**	**8.64%**	**93.27%**
Respiratory inorganics	**9.20%**	1.97%	1.42%	6.98%	1.21%	0.45%	**65.71%**	3.83%	**9.22%**	**84.14%**
Ionizing radiation	**42.81%**	2.75%	1.99%	**14.58%**	1.17%	**4.60%**	6.32%	4.76%	**21.02%**	**83.02%**
Ozone layer depletion	**41.83%**	2.70%	1.95%	8.40%	0.37%	0.60%	**31.02%**	0.24%	**12.89%**	**85.73%**
Respiratory organics	4.69%	1.06%	0.77%	3.15%	1.17%	1.44%	**65.09%**	**20.28%**	2.34%	**85.37%**
Aquatic ecotoxicity	**39.72%**	0.04%	0.03%	0.34%	**19.36%**	3.89%	**30.73%**	0.22%	5.67%	**89.81%**
Terrestrial ecotoxicity	**39.72%**	0.04%	0.03%	0.34%	**19.36%**	3.89%	**30.73%**	0.22%	5.67%	**89.81%**
Terrestrial acid/nutri	**14.50%**	3.34%	2.42%	**10.90%**	4.79%	0.26%	**43.28%**	**7.99%**	**12.52%**	**89.20%**
Land occupation	0.10%	0.00%	0.00%	**12.10%**	3.27%	**69.92%**	5.89%	2.76%	5.96%	**82.02%**
Aquatic acidification	**7.89%**	1.44%	1.04%	**27.39%**	1.80%	3.14%	**38.81%**	6.18%	**12.31%**	**86.40%**
Aquatic eutrophication	**10.43%**	0.66%	0.47%	**24.82%**	0.14%	1.82%	**51.15%**	2.76%	7.75%	**86.40%**
Global warming	**11.23%**	0.70%	0.50%	**11.29%**	0.11%	0.33%	**59.33%**	9.15%	7.36%	**81.86%**
Non-renewable energy	**17.07%**	1.09%	0.79%	3.94%	0.17%	0.53%	**31.62%**	**35.27%**	9.52%	**83.96%**
Mineral extraction	0.03%	0.00%	0.00%	0.01%	0.06%	0.00%	**99.75%**	0.05%	0.10%	**99.75%**

Figure 63. Normalised results of impact assessment related to the C&DW management system in the base case scenario, obtained by using normalised factors for Europe of Impact 2002+ methodology.



The contribution analyses for the selected impact categories are available in Appendix 5 (Figures A5.1 to A5.5). Table 53 reports the important stages, elementary flows and processes for each of the five selected categories.

The generated impacts on the environment of steel recycling are related to emissions of aromatic hydrocarbons from the EAF process for “Carcinogens” and to emissions of arsenic into soil and water for “Non-Carcinogens”. The emission of arsenic into soil derives from an herbicide used in sugarcane cropping, as the sugarcane bagasse is used as biomass in the Brazilian energy mix[8], while the emission of arsenic into water is related to the landfilling of the dust that is generated in the EAF process.

On the other hand, steel recycling determines remarkable avoided impacts for “Respiratory Inorganics”, mainly due to the avoided emissions of $PM_{2.5}$ related to the production of coke used in the BOF process. The avoided consumption of coke also contributes for “Non-Renewable Energy”, due to the coal mining to obtain coke. For “Global Warming”, the considerable avoided impacts refer to carbon dioxide emissions from pig iron production.

The impact of plastics recycling for “Non-Carcinogens” is due to emissions of arsenic into soil related to the electricity consumption in the recycling process. The avoided

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[8] Appendix 9 reports an analysis on the environmental impacts from the Brazilian energy mix.

impact for “Carcinogens” is related to aromatic hydrocarbons emission, mainly from the production of HDPE granulates. The remarkable contribution for “Non-Renewable Energy” indicates that plastics recycling saves the use of crude oil and natural gas, which also justifies the avoided impact for “Global Warming” category.

The avoided impacts of glass recycling for “Non-Renewable Energy”, “Respiratory Inorganics” and “Global Warming” are related to the avoided consumption of diesel and emissions of $PM_{2.5}$, SO_2, NO_x and CO_2, resulting from the production of primary glass. For “Non-Carcinogens”, the emission of arsenic into the soil is due to the spreading of the wastewater sludge from the primary glass production.

The diesel used in the inert landfill operation is the main responsible for “Respiratory Inorganics”, due to emissions of NO_x and $PM_{2.5}$, and for “Non-Renewable Energy” category. The emission of methane biogenic from paperboard waste landfilling is the main reason for the impact of “Global Warming”.

Transport are significant mainly for “Global Warming”, due to emissions of carbon dioxide, and for “Respiratory Inorganics”, due to emissions of NO_x and $PM_{2.5}$, the latter coming from tyre wear emissions.

Table 53. Main data obtained from contribution analysis of life cycle impact assessment results acquired by Impact 2002+.

Impact categories	Important stages	Important elementary flows	Important processes
Respiratory inorganics	Steel recycling (-)	🟦 $PM_{2.5}$	Coke production
	Glass recycling (-)	🟦 $PM_{2.5}$, SO_2 and NO_X	Primary glass production (without cullets)
	Transport (+)	🟦 Nitrogen oxides	Transport, freight, lorry 16-32 metric ton (EURO4)
		🟦 $PM_{2.5}$	Tyre wear emissions from trucks
Global warming	Steel recycling (-)	🟦 Carbon dioxide (fossil)	Pig iron production
	C&DW landfilling (+)	🟦 Methane (biogenic)	Paperboard waste landfilling
	Transport (+)	🟦 Carbon dioxide (fossil)	Transport, lorry 16-32 metric ton (EURO4)
Carcinogens	Plastics recycling (-)	🟦 Hydrocarbons, aromatic	HDPE granulate production
	Steel recycling (+)		Steel recycling process by electric arc furnace
Non-renewable energy	Steel recycling (-)	🟨 Hard coal	Hard coal mine operation
	Plastics recycling (-)	🟨 Crude oil Natural gas	PVC suspension polymerised and HDPE granulate production
	Transport (+)	🟨 Crude oil	Petroleum production
Non-carcinogens	Glass recycling (-)	🟧 Arsenic	Wastewater from primary glass production
	Steel recycling (+)	🟧 Arsenic	Sugarcane production (Brazilian energy mix)
		🟩 Arsenic	Landfilling of dust generated in the steel recycling process by electric arc furnace
	Plastics recycling (+)	🟧 Arsenic	Sugarcane production (Brazilian energy mix)

Legend

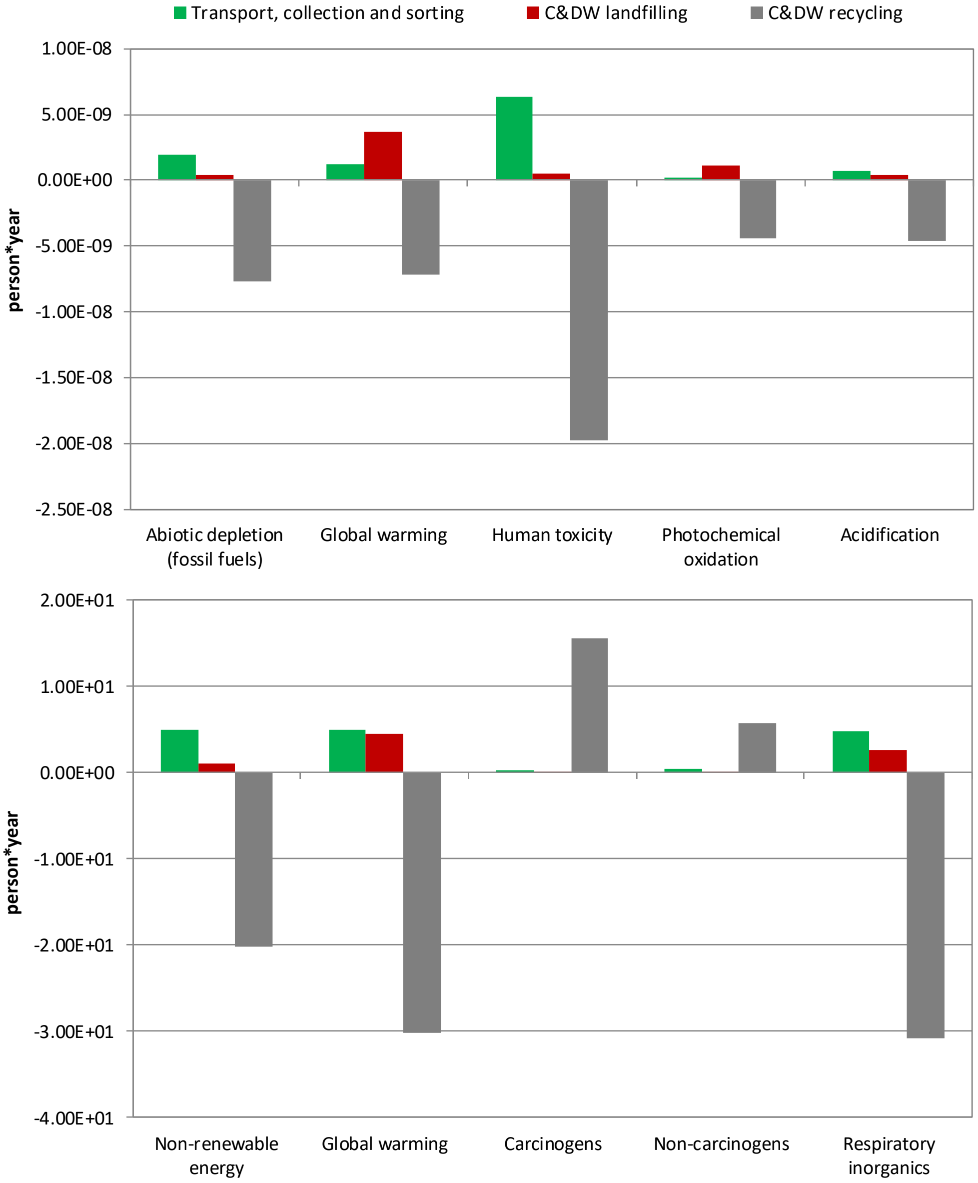
(+) Environmental impact (-) Avoided environmental impact

🟦 Emission into air 🟧 Emission into soil 🟩 Emission into water 🟨 Raw material

5.3 COMPARISON OF THE LCIA RESULTS OBTAINED BY CML BASELINE AND IMPACT 2002+

Figure 64 present the normalised results considering the three main stages of the C&DW management system, according to the selected impact categories of CML baseline and Impact 2002+ methodologies, respectively. The results indicate the great importance of C&DW recycling. Its role is not only related to the diversion of materials from landfill, but also mainly to the avoided impacts from recovered materials.

Figure 64. Normalised results of impact assessment for the three main stages of C&DW management system in the base case scenario, obtained by using normalised factors for World of CML baseline methodology (top) and for Europe of Impact 2002+ methodology (bottom).



There is a fair similarity between the results related to the following pairs of impact categories: "Abiotic Depletion (fossil fuels)" and "Non-Renewable Energy"; "Global Warming"; "Acidification" and "Respiratory Inorganics". However, the results of "Human Toxicity" of CML baseline and "Human Toxicity" ("Carcinogens" and "Non-Carcinogens") of Impact 2002+ are not directly comparable.

Figures from 64 to 67 allow to analyse all these results in detail, by showing the process contribution to a specific impact category of each C&DW management stage, as obtained by using the two methodologies.

Transport is the main contributor for the generated impacts on the environment for "Abiotic Depletion (fossil fuels)" of CML baseline and for "Non-Renewable Energy" of Impact 2002+ (Figure 65), since both attribute the same importance to the consumption of crude oil. With reference to the avoided impacts, the stages that provide the main contributions are those of steel recycling and plastics recycling. The avoided impacts of steel recycling are related to the avoided consumption of coal, while those of plastics recycling correspond to avoided consumption of crude oil and natural gas.

Figure 65. Percentage contribution of each management stage to the generated and/or to the avoided impacts for "Abiotic Depletion (fossil fuels)" and "Non-Renewable Energy". Data related to the characterisation analyses of base case scenario.

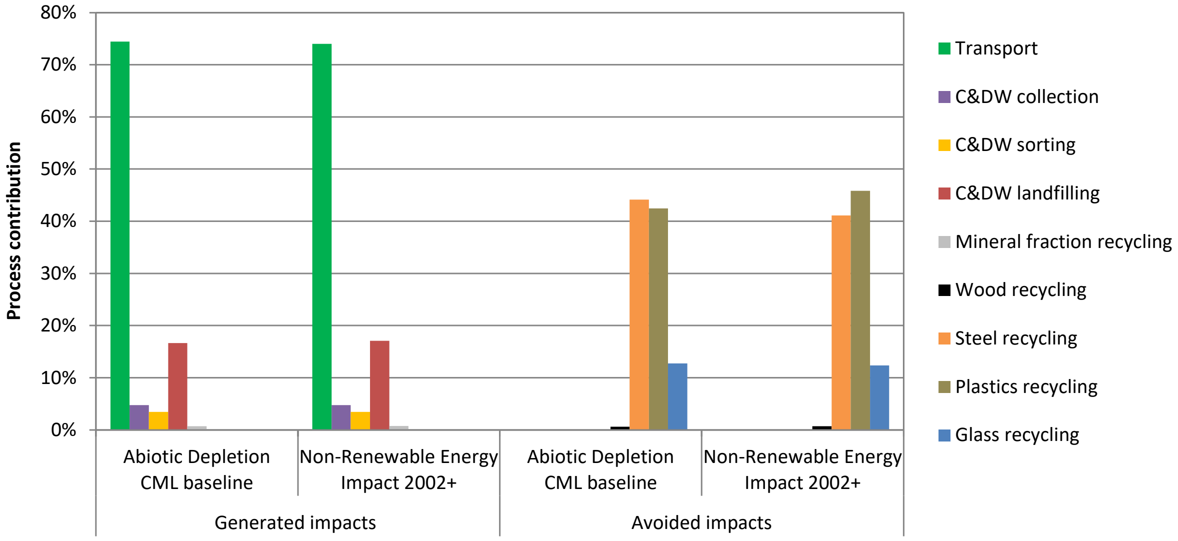


Figure 66 shows that C&DW landfilling provides the greatest contribution for "Global Warming". This is mainly due to the emission of biogenic methane from paperboard waste landfilling, whatever methodology (Figure A4.7 – Appendix A; Figure A5.6 – Appendix 5). The characterisation factor of biogenic methane is 22.25 $kgCO_2eq.kg^{-1}$ in CML baseline and 4.85 $kgCO_2eq.kg^{-1}$ in Impact 2002+, which justifies the difference between the results. It is important to note that paperboard waste accounts for less than 5% on mass basis of the total C&DW landfilling, but it contributes to 67% and 33% of the total impacts of "Global Warming" according to the results obtained by CML baseline and Impact 2002+, respectively. Both methodologies highlight that transport provides a remarkable contribution even for this category.

The avoided impacts in "Global Warming" of steel recycling are always related to the emission of carbon dioxide from pig iron production. The avoided impacts of plastics and glass recycling are instead due to the emission of carbon dioxide from the production of primary plastics (mainly PVC) and glass.

Figure 66. Percentage contribution of each management stage to the generated and/or to the avoided impacts for "Global Warming". Data related to the characterisation analyses of base case scenario.

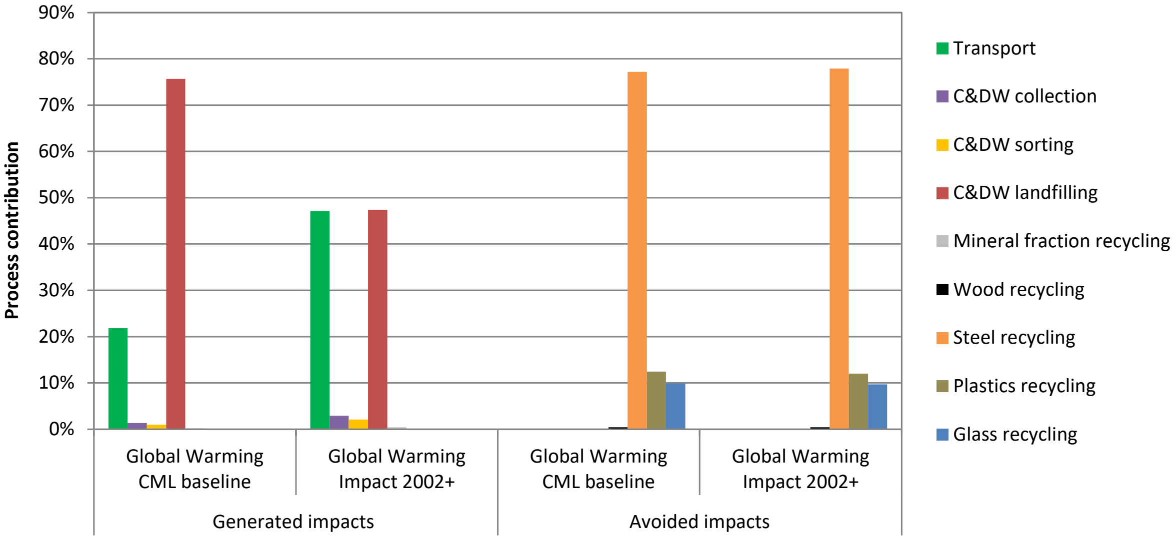


Figure 67 reports the results related to the categories of "Acidification" and "Respiratory Inorganics". There is again a large contribution of transport and C&DW landfilling for the generated impacts, since both are related to emissions of nitrogen oxides, which have comparable significance in both methodologies. With reference to the avoided impacts, the two methodologies indicate the main contribution of steel recycling. For CML this is due to emission of sulphur dioxide related to sinter iron production, while for Impact 2002+ this is mainly due to the emission of $PM_{2.5}$ related to coke production. The contributional analysis for "Respiratory Inorganics" of Impact 2002+ (Figure A5.1 - Appendix 5) indicates the emission of sulphur dioxide as the third most important elementary flow, which is in agreement to the result of CML. It is important to note that in the CML methodology there is no characterisation factor for $PM_{2.5}$ flow, but there is a factor for PM_{10}. The avoided impacts of plastics and glass recycling are related to avoided emission of sulphur dioxide in the production of their virgin materials. The contributions are higher in CML because this methodology attributes major importance to sulphur dioxide emission. The minor contribution of mineral fraction recycling to the avoided impacts is mainly due to emissions of nitrogen oxides, which are generated during the blasting process required in the basalt extraction.

Figure 67. Percentage contribution of each management stage to the generated and/or to the avoided impacts for "Acidification" and "Respiratory Inorganics". Data related to the characterisation analyses of base case scenario.

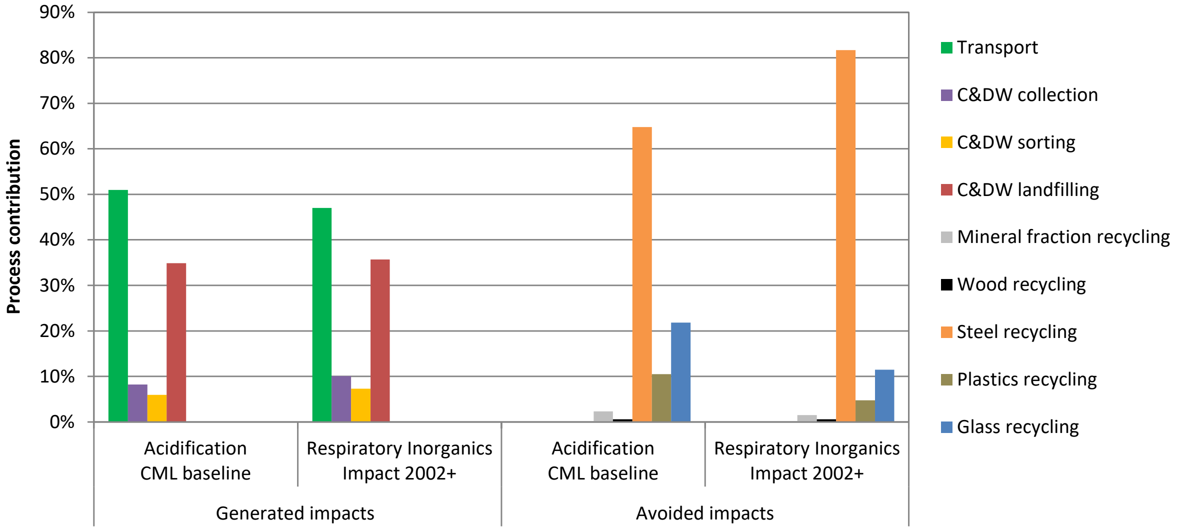


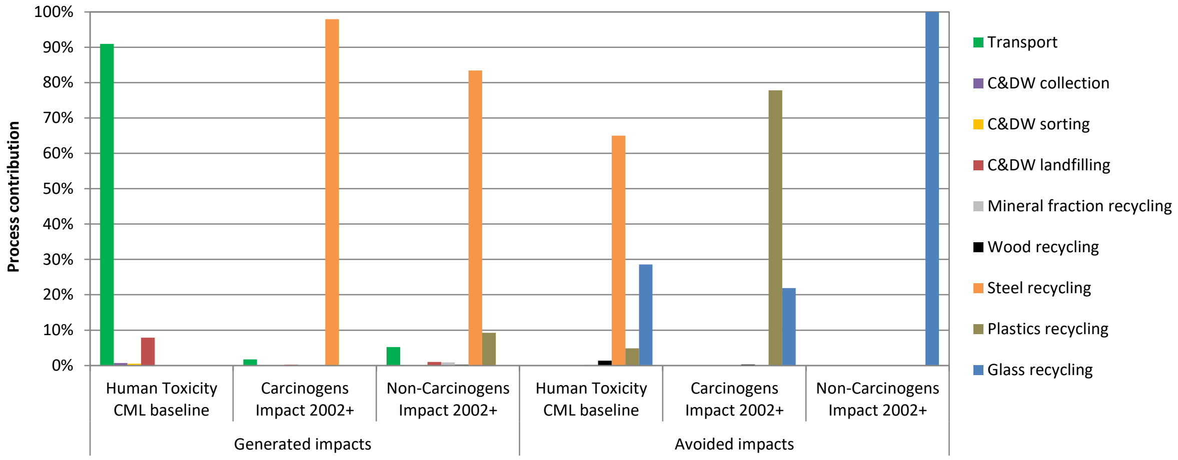
Figure 68 indicates that, according to the results of "Human Toxicity" (CML baseline), transport is the most important stage for the generated impacts and, steel recycling for the avoided impacts. On the other hand, according to the results of "Carcinogens" and "Non-Carcinogens" (Impact 2002+), steel recycling is the most important stage for the generated impacts and, glass and plastics recycling for the avoided impacts.

The results obtained by Impact 2002+ report the generated impacts of steel recycling due to emissions of aromatic hydrocarbons for "Carcinogens" and emissions of arsenic into water and soil for "Non-Carcinogens". Aromatic hydrocarbons emissions do not appear in the results obtained by CML baseline, due to the absence of a generic characterisation factor for this flow. There is a characterisation factor only for the emission of arsenic into water in CML, but the value is not significant.

The results obtained by CML baseline report the avoided impacts of steel recycling due to air emission of benzene (Figure A4.2 - Appendix A). Although this emission also appears as avoided in the results obtained by Impact 2002+ (Figure A5.3 - Appendix 5), the generated emissions of aromatic hydrocarbons (from recycling process) are higher than those of benzene (from primary steel production). For this reason, the final result does not provide avoided impacts related to the steel recycling for “Carcinogens”.

The avoided impacts of glass and plastics recycling for “Carcinogens” correspond to the avoided emissions of aromatic hydrocarbons in the production of primary plastics and glass. Glass recycling is the only contributor for the avoided impacts of “Non-Carcinogens” and the second most important for “Human Toxicity”. For CML baseline, the contribution is related to the avoided air emission of selenium in the primary glass production (Figure A4.2 – Appendix 4), while for Impact 2002+, it is related to electricity energy saving (represented by the avoided emission of arsenic into the soil in Figure A5.5 – Appendix 5).

Figure 68. Percentage contribution of each management stage to the generated and/or to the avoided impacts for “Human Toxicity”, “Carcinogens” and “Non-Carcinogens”. Data related to the characterisation analyses of base case scenario.



In summary, it is possible to observe that: (i) there is a general agreement in the results obtained with the two methodologies with reference to “Abiotic Depletion (fossil fuels)/”Non-Renewable Energy”, “Global Warming”, “Acidification”/Respiratory Inorganics”; (ii) the results of CML methodology for “Human Toxicity” cannot be directly compared with those of “Carcinogens” + “Non-Carcinogens” obtained by Impact 2002+; (iii) transport is the main contributor for the generated impacts of “Abiotic Depletion (fossil fuels)” and “Non-Renewable Energy”; (iv) C&DW landfilling provides the greatest contribution for the generated impacts of “Global Warming”; (v) steel recycling is the main contributor for the avoided impacts of “Global Warming”, “Acidification” and “Respiratory Inorganics”.

5.4. INTERPRETATION

In this LCA stage, a sensitivity analysis was developed by two criteria: (i) assessing the LCIA results related to alternative scenarios and base case scenario and, (ii) analysing the effect of variations of some selected input data.

Scenarios analysis consists in verifying different options individually and observing the effect of these changes on the final result (CLAVREUL; GUYONNET; CHRISTENSEN, 2012). In this study, the evaluation of alternative scenarios aims to analyse changes in the environmental profile of the C&DW management systems due to the increase of recycling rates and determine in which scenarios this strategy provides environmental benefits.

The main parameters that can affect the LCIA results of this study are: C&DW composition, transport stages, recycling rates, recycling efficiency (including sorting and reprocessing stages), recycling technology, substitute material and substitution ratio assumed for each recovered material, and landfill modelling.

In particular, C&DW composition, transport stages and landfill modelling were defined as the most important for this study. The C&DW composition analysis is important due to the differences between the data provided by the municipalities (see Table 15), which may lead to uncertainties in the final results. Transport stages were one of the the main contributors for almost all impact categories for both LCIA methodologies, consisting of an important parameter to define the environmental profile of C&DW management systems. Landfilling modeling was considered due to its meaningful influence on the results obtained by CML baseline methodology.

The effects of transport stages were evaluated considering the mineral fraction management, which is the most representative. The existence of few recycling facilities increases the transport distances, making the mineral fraction the largest contributor to the transport stages. The results of this analysis are reported in the analysis of alternative scenarios 3.1 and 3.2. In addition, the standard of emissions from trucks were evalatuted, considering the use of trucks EURO 3 and EURO 5 instead of EURO 4, and the results does not provide significative differences (Figures A6.1 and A6.2 – Appendix 6). The analysis of the variation data related to C&DW composition and landfill modelling are reported in the sections 5.4.1.3 and 5.4.1.4 respectively.

5.4.1 LIFE CYCLE IMPACT ASSESSMENT OF ALTERNATIVE SCENARIOS

The alternative management scenarios were elaborated focusing on the mineral fraction waste (see section 4.3.1.5). Appendix 6 reports the main data of mineral fraction management, specially the transport distances, quantities of C&DW recycled, landfilled and stored, diesel and electricity consumptions.

5.4.1.1 ALTERNATIVE SCENARIOS 1 AND 2

The characterised results related to the base case scenario and those related to the alternative scenarios are reported in terms of variation factor (VF), which has been defined by Ardolino *et al*. (2018) as the ratio between the results for the alternative scenario and the base case scenario. A variation factor equal to 1 indicates no variation; some variations occur when VF<1 or VF>1; and a negative value of VF indicates a modification of the potential impact from positive to negative or viceversa. For example, when the result of the base case scenario of a certain impact category is negative, VF>1 indicates larger environmental benefits. In other words, it indicates the increase of the avoided impacts and, therefore, the reduction of generated impacts of the category. When the result of the base case scenario of a certain impact category is positive, VF>1 indicates the increase of the impacts of the category analysed. These data are listed in Tables 54 and 55, as obtained by means of CML baseline and Impact 2002+ methodologies, respectively.

Table 54. Characterised results of the base case scenario and the results of the alternative scenarios in terms of variation factor. Data obtained by CML baseline.

Impact category	**Base case scenario**	**Alternative scenarios and recycling rates (%)**									
		1a	**1b**				**2a**	**2b**			
	20	**20**	**40**	**60**	**80**	**100**	**20**	**40**	**60**	**80**	**100**
Abiotic depletion (fossil fuels) (MJ)	-2.00E+06	1.03	1.03	1.03	1.02	1.02	1.04	1.04	1.04	1.04	1.04
Global warming (kg CO_2 eq)	-9.71E+04	1.05	1.04	1.04	1.04	1.03	1.05	1.06	1.06	1.07	1.07
Human toxicity (kg 1,4-DB eq)	-3.30E+04	1.01	1.01	1.02	1.02	1.03	1.01	1.02	1.03	1.04	1.04
Photochemical Oxidation (kg C_2H_4 eq)	-1.14E+02	1.01	1.01	1.01	1.01	1.02	1.01	1.02	1.02	1.02	1.03
Acidification (kg SO_2 eq)	-8.55E+02	1.05	1.09	1.13	1.17	1.21	1.06	1.11	1.16	1.21	1.26

Table 55. Characterised results of the base case scenario and the results of the alternative scenarios in terms of variation factor. Data obtained by Impact 2002+.

Impact category	Base case scenario	Alternative scenarios and recycling rates (%)									
		1a	**1b**				**2a**	**2b**			
	20	**20**	**40**	**60**	**80**	**100**	**20**	**40**	**60**	**80**	**100**
Non-renewable energy (MJ)	-2.16E+06	1.03	1.03	1.02	1.02	1.02	1.03	1.04	1.04	1.04	1.04
Global warming (kg CO_2 eq)	-2.06E+05	1.02	1.02	1.02	1.02	1.01	1.02	1.03	1.03	1.03	1.03
Carcinogens (kg C_2H_3Cl eq)	4.02E+04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Non-carcinogens (kg C_2H_3Cl eq)	1.57E+04	1.00	1.01	1.02	1.03	1.04	0.99	1.00	1.00	1.01	1.01
Respiratory inorganics (kg $PM_{2.5}$ eq)	-2.36E+02	1.05	1.08	1.11	1.14	1.16	1.06	1.10	1.14	1.17	1.21

The results indicate that the increase of the mineral fraction recycling and the production of medium quality recycled aggregates improve significantly the impact categories of “Acidification” and “Respiratory Inorganics” with reference to the base case scenario. For these categories, scenarios 2a and 2b provide a reduction in the impacts of 6% and 26% in CML, and 6% and 21% in Impact 2002+, respectively, while scenarios 1a and 1b provide a reduction of 5% and 21% in CML, and 5% and 16% in Impact 2002+.

In the scenarios 2a and 2b the recycling facilities produce higher amount of medium quality recycled aggregate, which substitute a larger amount of natural aggregates, avoiding air emissions of ammonia, nitrogen oxides and $PM_{2.5}$ related to the basalt extraction (Figures A6.3 and A6.4 – Appendix 6).

In both methodologies, the increase of the recycling rates improves the impact categories “Abiotic Depletion (fossil fuels)”, “Global Warming” and “Non-Renewable Energy” only in scenarios 2a and 2b. In scenarios 1a and 1b this does not occur because the higher the recycling rates, the greater are the diesel consumption (Table A6.1 – Appendix A).

It is important to note that in the scenarios 2, it was assumed that the recycling facilities consume the lowest possible amount of diesel in order to produce the higher amount of medium quality aggregates. Thus, considering the results of “Global Warming”, “Abiotic Depletion (fossil fuels)” and “Non-Renewable Energy”, in both methodologies scenarios 2a and 2b appear as a better solution.

Although the increase in recycling rates decreases the need of inert landfilling and, therefore, decreases the diesel consumption used in the landfill operation, this reduction is not significant in the overall management system.

5.4.1.2 ALTERNATIVE SCENARIOS 3.1 AND 3.2

Tables 56 and 57 show the results of base case scenario and alternative scenarios (1, 3.1 and 3.2) in terms of variation factor, obtained by using CML and Impact 2002+ methodologies. The comparison of the alternative scenario 3.1a (20%) and the base case scenario indicates “Human Toxicity” as the most influenced category, with an increase of 13% in the impacts. However, the result of this category is still negative, which means avoided impacts. It is also possible to note a slight increase of the impacts for “Abiotic Depletion (fossil fuels)” (5%), “Non-Renewable Energy” (5%) and “Global Warming” (7% in CML and 3% in Impact 2002+). This results confirm the environmental feasibility of the use of the recycling facilities currently in operation, instead of the disposal of the mineral fraction into inert landfills, despite the transport distances.

The comparison of alternative scenarios 3.1b (100%) and 1b (100%) with the base case scenario, also indicates “Human Toxicity” as the most influenced category, with an increase of 11% in the impacts of the alternative scenario 3.1b (100%). This comparison reveals a slight increase of the impacts for “Abiotic Depletion (fossil fuels)” (6%), “Non-Renewable Energy” (6%) and “Global Warming” (8% in CML and 4% in Impact 2002+). As the previous case, the increase of impacts is not so high, then, it is possible to confirm that the use of recycling facilities currently in operation can be an alternative, instead of constructing new ones. It is important to note that the impacts related to the construction of new recycling facilities were not considered.

The comparison between alternative scenarios 3.1 and 3.2 reveals that the transport of the mineral fraction that will be effectively recycled to the recycling facility, and the transport of the remaining fraction to an inert landfill, provides minor variations in the impacts.

Table 56. Characterised results of base case scenario and alternative scenarios (1, 3.1 and 3.2) in terms of variation factor. Data obtained by CML baseline.

Impact category	**Base case scenario**	**Alternative scenarios and recycling rates (%)**														
		1a	**1b**				**3.1a**	**3.1b**				**3.2a**	**3.2b**			
	20%	**20**	**40**	**60**	**80**	**100**	**20**	**40**	**60**	**80**	**100**	**20**	**40**	**60**	**80**	**100**
Abiotic depletion (fossil fuels) (MJ)	-2.00E+06	1.03	1.03	1.03	1.02	1.02	0.95	0.95	0.94	0.94	0.94	0.98	0.96	0.95	0.94	0.95
Global warming (kg CO_2 eq)	-9.82E+04	1.05	1.04	1.04	1.04	1.03	0.93	0.93	0.93	0.92	0.92	0.97	0.95	0.94	0.92	0.93
Human toxicity (kg 1,4-DB eq)	1.18E+05	1.00	1.00	0.99	0.99	0.99	0.87	0.87	0.88	0.88	0.89	0.95	0.93	0.91	0.89	0.87
Photochemical Oxidation (kg C_2H_4 eq)	-1.14E+02	1.01	1.01	1.01	1.01	1.02	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Acidification (kg SO_2 eq)	-8.55E+02	1.05	1.09	1.13	1.17	1.21	1.00	1.04	1.08	1.12	1.16	1.05	1.08	1.12	1.16	1.00

Table 57. Characterised results of base case scenario and alternative scenarios (1, 3.1 and 3.2) in terms of variation factor. Data obtained by Impact 2002+.

Impact category	**Base case scenario**	**Alternative scenarios and recycling rates (%)**														
		1a	**1b**				**3.1a**	**3.1b**				**3.2a**	**3.2b**			
	20	**20**	**40**	**60**	**80**	**100**	**20**	**40**	**60**	**80**	**100**	**20**	**40**	**60**	**80**	**100**
Non-renewable energy (MJ)	-2.16E+06	1.03	1.03	1.02	1.02	1.02	0.95	0.95	0.95	0.94	0.94	0.99	0.98	0.97	0.95	0.94
Global warming (kg CO_2 eq)	-2.06E+05	1.02	1.02	1.02	1.02	1.01	0.97	0.97	0.97	0.96	0.96	0.99	0.99	0.98	0.97	0.96
Carcinogens (kg C_2H_3Cl eq)	4.02E+04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Non-carcinogens (kg C_2H_3Cl eq)	1.57E+04	1.00	1.01	1.02	1.03	1.04	1.02	1.03	1.04	1.05	1.06	1.01	1.02	1.03	1.05	1.06
Respiratory inorganics (kg $PM_{2.5}$ eq)	-2.36E+02	1.05	1.08	1.11	1.14	1.16	1.01	1.03	1.06	1.08	1.11	1.01	1.03	1.06	1.08	1.11

5.4.1.3 SENSITIVITY ANALYSIS OF VARIATIONS IN THE C&DW COMPOSITION

The waste composition has fundamental influence on environmental emissions associated with waste treatment, recycling and disposal, and may affect the LCA results of waste management systems (BISINELLA *et al.*, 2017). The study about the influence of variations in the C&DW composition used in the base case scenario is crucial due to the lack of data about this parameter and the variations in the available data (see Table 15).

The analysis of the C&DW compositions presented in Table 15 reveals that wood, gypsum and mixed waste are the main fractions that may vary among the C&DW generated in the municipalities and that three municipalities consider steel, glass, plastics and paperboard in the same category (recyclable fraction). For this reason, it was decided to analyse the variation in the weight-percentage of these fractions.

In the variation of a specific C&DW fraction, the mineral fraction (MixC&DW) was increased or decreased in order to maintain the total as 100%, keeping the quantities of the other fractions fixed. The following assumptions were considered to perform a systematic analysis of variations in the C&DW composition:

- Increase from 10% to 100% of **wood** in relation to its weight-percentage in the composition used in the base case scenario (Table A7.1 – Appendix 7).
- Include from 1% to 10% of **gypsum** in relation to its weight-percentage in the composition used in the base case scenario (Table A7.2 – Appendix 7).
- Increase from 10% to 1000% of **mixed waste** in relation to its weight-percentage in the composition used in the base case scenario (Table A7.3 – Appendix 7).
- Decrease from 10% to 100% of **steel** in relation to its weight-percentage in the composition used in the base case scenario (Table A7.4 – Appendix 7).
- Variation from -100% to +100% of **glass** in relation to its weight-percentage in the composition used in the base case scenario (Table A7.5 – Appendix 7).
- Variation from -100% to +100% of **plastics** in relation to its weight-percentage in the composition used in the base case scenario (Table A7.6 – Appendix 7).
- Variation from -100% to +100% of **paperboard** in relation to its weight-percentage in the composition used in the base case scenario (Table A7.7 – Appendix 7).

The variations in the weight-percentage of a specific fraction may influence other stages of the C&DW system, for example, the transport units (tkm). The changes required for each variation in the composition are detailed in Tables A7.8 to A7.14 (Appendix 7).

Tables 58 and 59 show the characterised results obtained with the variations of the weight-percentage of wood (from +10% to +100%) in relation to the composition used in the base case scenario. The results indicate that the increase of wood in the C&DW composition does not affect the results of both LCIA methodologies, since the variation factors for all impact categories are close to 1.

Table 58. Characterised results of the base case scenario and the results of the variations from +10% to +100% of wood in relation to its weight-percentage in the reference composition in terms of variation factor. Data obtained by CML baseline.

Impact category	Base case	Variation in the weight-percentage of wood									
	3.70% of wood	+10%	+20%	+30%	+40%	+50%	+60%	+70%	+80%	+90%	+100%
Abiotic depletion (fossil fuels) (MJ)	-2.00E+06	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99
Global warming (kg CO_2 eq)	-9.71E+04	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.98
Human toxicity (kg 1,4-DB eq)	-3.30E+04	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Photochemical Oxidation (kg C_2H_4 eq)	-1.14E+02	1.00	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.02	1.02
Acidification (kg SO_2 eq)	-8.55E+02	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99

Table 59. Characterised results of the base case scenario and the results of the variations from +10% to +100% of wood in relation to its weight-percentage in the reference composition in terms of variation factor. Data obtained by Impact 2002+.

Impact category	Base case	Variation in the weight-percentage of wood									
	3.70% of wood	+10%	+20%	+30%	+40%	+50%	+60%	+70%	+80%	+90%	+100%
Non-renewable energy (MJ)	-2.16E+06	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99
Global warming (kg CO_2 eq)	-2.06E+05	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99
Carcinogens (kg C_2H_3Cl eq)	4.02E+04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Non-carcinogens (kg C_2H_3Cl eq)	1.57E+04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.01	1.01
Respiratory inorganics (kg $PM_{2.5}$ eq)	-2.36E+02	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99

Tables 60, 61, 62 and 63 show the characterised results obtained with the inclusion of gypsum in the C&DW composition (from 1% to 10%). The results reported in Tables 67 and 68 refer to the current management practice, considering that the gypsum wastes are sent to landfills authorized to receive industrial wastes classified as non-inert. The results indicate that the existence of gypsum in the C&DW composition does not affect the results of both methodologies.

There are recycling alternatives for this type of waste, in which the secondary product obtained can be used in agriculture or clinker production (DRYWALL, 2009). Currently, the recycled gypsum is those obtained from the waste generated by large construction companies, due to the higher generation rates and quality (absence of impurities). In this context, recycling alternatives for gypsum waste were not considered in this sensitivity analysis, since they are not applied to small C&DW generators, and consequently to the municipal C&DW management.

Table 60. Characterised results of the base case scenario and the results of the addition from 1% to +10% of gypsum in relation to its weight-percentage in the reference composition in terms of variation factor. Data obtained by CML baseline.

Impact category	Base case	Variation in the weight-percentage of gypsum									
	0% of gypsum	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Abiotic depletion (fossil fuels) (MJ)	-2.00E+06	1.00	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.97	0.97
Global warming (kg CO_2 eq)	-9.71E+04	1.00	0.99	0.99	0.98	0.98	0.98	0.97	0.97	0.96	0.96
Human toxicity (kg 1,4-DB eq)	-3.30E+04	1.00	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.97	0.97
Photochemical Oxidation (kg C_2H_4 eq)	-1.14E+02	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99
Acidification (kg SO_2 eq)	-8.55E+02	1.00	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.97	0.97

Table 61. Characterised results of the base case scenario and the results of the addition from 1% to +10% of gypsum in relation to its weight-percentage in the reference composition in terms of variation factor. Data obtained by Impact 2002+.

Impact category	Base case	Variation in the weight-percentage of gypsum									
	0% of gypsum	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Non-renewable energy (MJ)	-2.16E+06	1.00	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.97	0.97
Global warming (kg CO_2 eq)	-2.06E+05	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.98
Carcinogens (kg C_2H_3Cl eq)	4.02E+04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Non-carcinogens (kg C_2H_3Cl eq)	1.57E+04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Respiratory inorganics (kg $PM_{2.5}$ eq)	-2.36E+02	1.00	0.99	0.99	0.99	0.98	0.98	0.98	0.97	0.97	0.97

In some cases, the gypsum waste can be sent to sanitary landfills due to inefficiency of the management system. When gypsum ($CaSO_4 \cdot 2H_2O$) is disposed along with biodegradable wastes, the dissolved sulphate (SO_4^{2-}) will be metabolised by the anaerobic microbes in the landfill and converted to sulphide (S^{2-}), which is mainly precipitated with iron ions (FeS) or it can be transferred to the landfill gas as dihydrogen sulphide (H_2S). In the second case, the H_2S

is oxidised to sulphur dioxide (SO_2) either by incineration or flaring of the landfill gas or by atmospheric oxidation (ALTHAUS *et al.*, 2004).

For this reason, Tables 69 and 70 present the results considering the final disposal of gypsum waste in sanitary landfills. The results indicate that the emissions of sulphur dioxide from gypsum landfilling affect significantly the categories of “Acidification”, “Human Toxicity” and “Photochemical Oxidation” of CML and “Respiratory Inorganics” and “Non-Carcinogens” of Impact 2002+.

According to the results obtained by CML, the existence of 1% of gypsum in the C&DW composition change the results of “Acidification” and “Human Toxicity” to positive, increasing the generated impacts of these categories by 323% and 165%, respectively. In relation to the results obtained by Impact 2002+, the existence of 2% of gypsum change the results of “Respiratory Inorganics” to positive, increasing the impact of this category by 153%.

The comparison of the results of “Acidification” (CML) and “Respiratory Inorganics” (Impact 2002+) indicate that the emissions of SO_2 are highly emphasised in CML methodology, which explain the difference in results. In CML, the existence of 10% of gypsum provides an increase of 3222% in the impacts, while in Impact 2002+ it provides an increase of 765%.

Table 62. Characterised results of the base case scenario and the results of the addition from 1% to +10% of gypsum in relation to its weight-percentage in the reference composition in terms of variation factor. Results considering the disposal of gypsum in sanitary landfills. Data obtained by CML baseline.

Impact category	**Base case**	**Variation in the weight-percentage of gypsum**									
	0% of gypsum	**1%**	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**
Abiotic depletion (fossil fuels) (MJ)	-2.00E+06	0.99	0.99	0.98	0.98	0.97	0.97	0.96	0.96	0.95	0.95
Global warming (kg CO_2 eq)	-9.71E+04	0.99	0.98	0.98	0.97	0.96	0.95	0.95	0.94	0.93	0.92
Human toxicity (kg 1,4-DB eq)	-3.30E+04	-0.65	-2.27	-3.92	-5.55	-7.19	-8.82	-10.46	-12.09	-13.74	-15.36
Photochemical Oxidation (kg C_2H_4 eq)	-1.14E+02	0.03	-0.93	-1.91	-2.87	-3.84	-4.80	-5.77	-6.73	-7.71	-8.67
Acidification (kg SO_2 eq)	-8.55E+02	-2.24	-5.44	-8.68	-11.89	-15.13	-18.33	-21.57	-24.77	-28.01	-31.22

Table 63. Characterised results of the base case scenario and the results of the addition from 1% to +10% of gypsum in relation to its weight-percentage in the reference composition in terms of variation factor. Results considering the disposal of gypsum in sanitary landfills. Data obtained by Impact 2002+.

Impact category	**Base case**	**Variation in the weight-percentage of gypsum**									
	0% of gypsum	**1%**	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**
Non-renewable energy (MJ)	-2.16E+06	1.00	0.99	0.99	0.98	0.98	0.97	0.97	0.96	0.96	0.95
Global warming (kg CO_2 eq)	-2.06E+05	1.00	0.99	0.99	0.99	0.98	0.98	0.98	0.97	0.97	0.96
Carcinogens (kg C_2H_3Cl eq)	4.02E+04	1.00	1.00	1.00	1.00	1.01	1.01	1.01	1.01	1.01	1.01
Non-carcinogens (kg C_2H_3Cl eq)	1.57E+04	1.03	1.05	1.08	1.10	1.13	1.15	1.18	1.20	1.23	1.25
Respiratory inorganics (kg $PM_{2.5}$ eq)	-2.36E+02	0.23	-0.53	-1.29	-2.05	-2.82	-3.58	-4.34	-5.10	-5.87	-6.63

Tables 64 and 65 show the characterised results obtained with the variations of the weight-percentage of mixed wastes (from +10% to +1000%) in relation to the composition used in the base case scenario. It was decided to analyse an extensive variation of this fraction due to the existence of a large amount of mixed wastes in the C&DW, mainly caused by the absence of sorting at the construction sites.

The increase of mixed waste in the C&DW composition hardly affects the results obtained by both methodologies. The increase of 1000% of mixed waste in the C&DW composition (19.8% of mixed waste) provides the increase of impacts of “Global Warming” (12% in CML and 6% in Impact 2002+), “Abiotic Depletion (fossil fuels)” (9%), “Non-Renewable Energy” (8%), “Acidification” (9%) and “Respiratory Inorganics” (10%). It is important to emphasize that this result does not mean that the mixed wastes landfilling does not bring serious consequences for the environmental performance of C&DW management, since there is a possibility of recovering glass, plastics, wood and other materials present in this fraction, which were not included in this analysis.

Tables 66 and 67 show the characterised results obtained with the variations of the weight-percentage of steel (from -10% to -100%) in relation to the composition used in the base case scenario. The results of both methodologies show that the decrease of steel in the composition increase the impacts of all impact categories, with exception of “Carcinogens” and “Non-Carcinogens”. The latter are influenced by air emissions and electricity consumption in EAF process, therefore, the decrease of steel recycling provides benefits for these categories.

Table 64. Characterised results of the base case scenario and the results of the variations from +10% to +1000% of mixed waste in relation to its weight-percentage in the reference composition in terms of variation factor. Data obtained by CML baseline.

Impact category	**Base case**	**Variation in the weight-percentage of mixed waste**																		
	1.80% of mixed	**+10%**	**+20%**	**+30%**	**+40%**	**+50%**	**+60%**	**+70%**	**+80%**	**+90%**	**+100%**	**+200%**	**+300%**	**+400%**	**+500%**	**+600%**	**+700%**	**+800%**	**+900%**	**+1000%**
Abiotic depletion (fossil fuels) (MJ)	-2.00E+06	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.98	0.97	0.96	0.96	0.95	0.94	0.93	0.92	0.91
Global warming (kg CO_2 eq)	-9.71E+04	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.96	0.95	0.94	0.93	0.91	0.90	0.89	0.88
Human toxicity (kg 1,4-DB eq)	-3.30E+04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.98	0.97	0.97	0.96	0.95	0.95	0.94	0.93
Photochemical Oxidation (kg C_2H_4 eq)	-1.14E+02	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.98
Acidification (kg SO_2 eq)	-8.55E+02	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.93	0.92	0.91

Table 65. Characterised results of the base case scenario and the results of the variations from +10% to +1000% of mixed waste in relation to its weight-percentage in the reference composition in terms of variation factor. Data obtained by Impact 2002+.

Impact category	**Base case**	**Variation in the weight-percentage of mixed waste**																		
	1.80% of mixed	**+10%**	**+20%**	**+30%**	**+40%**	**+50%**	**+60%**	**+70%**	**+80%**	**+90%**	**+100%**	**+200%**	**+300%**	**+400%**	**+500%**	**+600%**	**+700%**	**+800%**	**+900%**	**+1000%**
Non-renewable Energy (MJ)	-2.16E+06	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.98	0.97	0.97	0.96	0.95	0.94	0.93	0.92	0.92
Global warming (kg CO_2 eq)	-2.06E+05	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.98	0.98	0.97	0.97	0.96	0.95	0.95	0.94
Carcinogens (kg C_2H_3Cl eq)	4.02E+04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Non-carcinogens (kg C_2H_3Cl eq)	1.57E+04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.01	1.01	1.01
Respiratory Inorganics (kg $PM_{2.5}$ eq)	-2.36E+02	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92	0.91	0.90

The results obtained by CML baseline indicate that the decrease from 50% to 100% of steel makes the impacts of "Global Warming" positive (generated impacts), increasing the impacts by 119% to 237%, respectively. The results obtained by Impact 2002+ indicate that the decrease from 90% to 100% makes the impacts of "Global Warming" positive, increasing the impacts by 101% to 112%.

Table 66. Characterised results of the base case scenario and the results of the variations from -10% to -100% of steel in relation to its weight-percentage in the reference composition in terms of variation factor. Data obtained by CML baseline.

Impact category	Base case	Variation in the weight-percentage of steel									
	3.20% of steel	-10%	-20%	-30%	-40%	-50%	-60%	-70%	-80%	-90%	-100%
Abiotic depletion (fossil fuels) (MJ)	-2.00E+06	0.94	0.88	0.81	0.75	0.69	0.63	0.56	0.50	0.44	0.38
Global warming (kg CO_2 eq)	-9.71E+04	0.77	0.52	0.29	0.06	-0.19	-0.42	-0.66	-0.89	-1.14	-1.37
Human toxicity (kg 1,4-DB eq)	-3.30E+04	0.91	0.81	0.71	0.62	0.52	0.42	0.33	0.23	0.13	0.04
Photochemical Oxidation (kg C_2H_4 eq)	-1.14E+02	0.88	0.75	0.62	0.50	0.37	0.25	0.12	-0.01	-0.14	-0.26
Acidification (kg SO_2 eq)	-8.55E+02	0.92	0.83	0.75	0.67	0.58	0.50	0.42	0.34	0.25	0.17

Table 67. Characterised results of the base case scenario and the results of the variations from -10% to -100% of steel in relation to its weight-percentage in the reference composition in terms of variation factor. Data obtained by Impact 2002+.

Impact category	Base case	Variation in the weight-percentage of steel									
	3.20% of steel	-10%	-20%	-30%	-40%	-50%	-60%	-70%	-80%	-90%	-100%
Non-renewable energy (MJ)	-2.16E+06	0.94	0.89	0.83	0.77	0.72	0.66	0.60	0.55	0.49	0.43
Global warming (kg CO_2 eq)	-2.06E+05	0.89	0.78	0.66	0.55	0.44	0.33	0.22	0.11	-0.01	-0.12
Carcinogens (kg C_2H_3Cl eq)	4.02E+04	0.89	0.77	0.66	0.55	0.43	0.32	0.21	0.10	-0.02	-0.13
Non-carcinogens (kg C_2H_3Cl eq)	1.57E+04	0.91	0.81	0.72	0.63	0.54	0.45	0.35	0.26	0.16	0.07
Respiratory inorganics (kg $PM_{2.5}$ eq)	-2.36E+02	0.89	0.79	0.68	0.58	0.47	0.36	0.25	0.15	0.04	-0.07

Tables 68 and 69 present the characterised results obtained with the variations of the weight-percentage of glass (from -100% to +100%) in relation to the composition used in the base case scenario. The increase of glass in the composition provides the decrease of impacts of all impact categories.

According to the results obtained by CML, "Human Toxicity" is the main category affected by the variations of glass in the composition. For example, the inexistence of glass in the C&DW composition increase the impact by 42%.

The results of “Abiotic Depletion”/“Non-Rewable Energy”, “Global Warming” and “Acidification”/“Respiratory Inorganics” are similar and indicate that the inexistence of glass in the C&DW composition increase approximately 20% of the impacts of each category.

Table 68. Characterised results of the base case scenario and the results of the variations from -100% to +100% of glass in relation to its weight-percentage in the reference composition in terms of variation factor. Data obtained by CML baseline.

Impact category	**Base case**	**Variation in the weight-percentage of glass**									
	1.70% of glass	**-100%**	**-80%**	**-60%**	**-40%**	**-20%**	**+20%**	**+40%**	**+60%**	**+80%**	**+100%**
Abiotic depletion (fossil fuels) (MJ)	-2.00E+06	0.82	0.97	0.93	0.90	0.86	1.18	1.04	1.07	1.11	1.14
Global warming (kg CO_2 eq)	-9.71E+04	0.71	0.94	0.88	0.82	0.77	1.30	1.06	1.12	1.18	1.24
Human toxicity (kg 1,4-DB eq)	-3.30E+04	0.58	0.92	0.83	0.75	0.66	1.43	1.09	1.18	1.26	1.34
Photochemical Oxidation (kg C_2H_4 eq)	-1.14E+02	0.92	0.98	0.97	0.95	0.93	1.08	1.02	1.03	1.05	1.07
Acidification (kg SO_2 eq)	-8.55E+02	0.72	0.95	0.89	0.84	0.78	1.28	1.06	1.12	1.17	1.22

Table 69. Characterised results of the base case scenario and the results of the variations from -100% to +100% of glass in relation to its weight-percentage in the reference composition in terms of variation factor. Data obtained by Impact 2002+.

Impact category	**Base case**	**Variation in the weight-percentage of glass**									
	1.70% of glass	**-100%**	**-80%**	**-60%**	**-40%**	**-20%**	**+20%**	**+40%**	**+60%**	**+80%**	**+100%**
Non-renewable energy (MJ)	-2.16E+06	0.83	0.87	0.90	0.93	0.97	1.04	1.07	1.10	1.14	1.17
Global warming (kg CO_2 eq)	-2.06E+05	0.87	0.89	0.92	0.95	0.97	1.03	1.06	1.08	1.11	1.14
Carcinogens (kg C_2H_3Cl eq)	4.02E+04	1.03	1.03	1.02	1.01	1.01	0.99	0.99	0.98	0.97	0.97
Non-carcinogens (kg C_2H_3Cl eq)	1.57E+04	1.10	1.08	1.06	1.04	1.02	0.98	0.96	0.94	0.92	0.90
Respiratory inorganics (kg $PM_{2.5}$ eq)	-2.36E+02	0.86	0.89	0.91	0.94	0.97	1.03	1.06	1.09	1.12	1.15

Tables 70 and 71 present the characterised results obtained with the variations of the weight-percentage of plastics (from -100% to +100%) in relation to the composition used in the base case scenario. “Abiotic Depletion (fossil fuels)”/“Non-Renewable Energy” and “Global Warming” are the most influenced impact categories. The inexistence of plastics in the C&DW composition increase approximately 61% of impacts of “Abiotic Depletion (fossil fuels)”; 65% of “Non-Renewable Energy”; 29% of “Global Warming” in CML and 15% of “Global Warming” in Impact 2002+. On the other hand, the decrease of plastics in the composition decrease the impacts of “Non-Carcinogens”, due to the electricity consumption in the recycling process.

Table 70. Characterised results of the base case scenario and the results of the variations from -100% to +100% of plastics in relation to its weight-percentage in the reference composition in terms of variation factor. Data obtained by CML baseline.

Impact category	**Base case**	**Variation in the weight-percentage of plastics**									
	1.50% of plastics	**-100%**	**-80%**	**-60%**	**-40%**	**-20%**	**+20%**	**+40%**	**+60%**	**+80%**	**+100%**
Abiotic depletion (fossil fuels) (MJ)	-2.00E+06	0.39	0.51	0.62	0.76	0.88	1.12	1.24	1.36	1.49	1.61
Global warming (kg CO_2 eq)	-9.71E+04	0.71	0.77	0.82	0.89	0.94	1.06	1.11	1.17	1.23	1.29
Human toxicity (kg 1,4-DB eq)	-3.30E+04	0.94	0.95	0.96	0.98	0.99	1.01	1.03	1.04	1.05	1.06
Photochemical Oxidation (kg C_2H_4 eq)	-1.14E+02	0.95	0.96	0.97	0.98	0.99	1.01	1.02	1.03	1.04	1.05
Acidification (kg SO_2 eq)	-8.55E+02	0.87	0.90	0.92	0.95	0.97	1.02	1.05	1.07	1.10	1.13

Table 71. Characterised results of the base case scenario and the results of the variations from -100% to +100% of plastics in relation to its weight-percentage in the reference composition in terms of variation factor. Data obtained by Impact 2002+.

Impact category	**Base case**	**Variation in the weight-percentage of plastics**									
	1.50% of plastics	**-100%**	**-80%**	**-60%**	**-40%**	**-20%**	**+20%**	**+40%**	**+60%**	**+80%**	**+100%**
Non-renewable energy (MJ)	-2.16E+06	0.35	0.48	0.60	0.75	0.87	1.13	1.25	1.38	1.52	1.65
Global warming (kg CO_2 eq)	-2.06E+05	0.85	0.88	0.91	0.94	0.97	1.03	1.06	1.09	1.12	1.15
Carcinogens (kg C_2H_3Cl eq)	4.02E+04	1.12	1.10	1.07	1.05	1.02	0.98	0.95	0.93	0.90	0.88
Non-carcinogens (kg C_2H_3Cl eq)	1.57E+04	0.90	0.92	0.94	0.96	0.98	1.02	1.04	1.06	1.08	1.10
Respiratory inorganics (kg $PM_{2.5}$ eq)	-2.36E+02	0.94	0.96	0.97	0.98	0.99	1.01	1.02	1.03	1.04	1.06

Tables 72 and 73 present the characterised results obtained with the variations of the weight-percentage of paperboard (from -100% to +100%) in relation to the composition used in the base case scenario. “Global Warming” is the most influenced impact category. The increase of 80% and 100% of paperboard in the composition (2.16 and 2.40% of paperboard, respectively) makes the impact positive, increasing 112% and 140% of the impacts of Global Warming in CML. The results of Impact 2002+ for this category were not change to positive, but there is an increase of impacts by 15% for the composition with 2.4% of paperboard. This difference is due to the higher biogenic methane characterisation factor in the CML methodology compared to Impact 2002+.

Table 72. Characterised results of the base case scenario and the results of the variations from -100% to +100% of paperboard in relation to its weight-percentage in the reference composition in terms of variation factor. Data obtained by CML baseline.

Impact category	**Base case**	**Variation in the weight-percentage of paperboard**									
	1.20% of paperboard	**-100%**	**-80%**	**-60%**	**-40%**	**-20%**	**+20%**	**+40%**	**+60%**	**+80%**	**+100%**
Abiotic depletion (fossil fuels) (MJ)	-2.00E+06	1.01	1.01	1.01	1.01	1.00	1.00	1.00	0.99	0.99	0.99
Global warming (kg CO_2 eq)	-9.71E+04	2.42	2.14	1.85	1.58	1.29	0.72	0.45	0.16	-0.12	-0.40
Human toxicity (kg 1,4-DB eq)	-3.30E+04	1.03	1.02	1.02	1.01	1.01	0.99	0.99	0.98	0.98	0.97
Photochemical Oxidation (kg C_2H_4 eq)	-1.14E+02	1.33	1.27	1.20	1.13	1.07	0.94	0.87	0.80	0.74	0.68
Acidification (kg SO_2 eq)	-8.55E+02	1.03	1.02	1.02	1.01	1.01	0.99	0.99	0.98	0.98	0.97

Table 73. Characterised results of the base case scenario and the results of the variations from -100% to +100% of paperboard in relation to its weight-percentage in the reference composition in terms of variation factor. Data obtained by Impact 2002+.

Impact category	**Base case**	**Variation in the weight-percentage of paperboard**									
	1.20% of paperboard	**-100%**	**-80%**	**-60%**	**-40%**	**-20%**	**+20%**	**+40%**	**+60%**	**+80%**	**+100%**
Non-renewable energy (MJ)	-2.16E+06	1.01	1.01	1.01	1.01	1.00	1.00	0.99	0.99	0.99	0.99
Global warming (kg CO_2 eq)	-2.06E+05	1.15	1.12	1.09	1.06	1.03	0.97	0.94	0.91	0.88	0.85
Carcinogens (kg C_2H_3Cl eq)	4.02E+04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Non-carcinogens (kg C_2H_3Cl eq)	1.57E+04	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.01	1.01	1.01
Respiratory inorganics (kg $PM_{2.5}$ eq)	-2.36E+02	1.02	1.02	1.01	1.01	1.00	1.00	0.99	0.99	0.98	0.98

5.4.1.4 SENSITIVITY ANALYSIS OF LANDFILL MODELLING

This sensitivity analysis aims at discussing the difference verified in the LCIA results of CML baseline when long-term emissions from leachate are included. Long-term emissions are considered to happen beyond 100 years. Previous studies have been indicated that only a minor part of the harmful substances contained in waste are released to the environment after this period (DOKA, 2009).

According to Zampori *et al.* (2016) the models used to estimate long-term emissions are affected by a high uncertainty, since the temporal dynamics of these emissions are difficult to predict over such long timespans (DOKA, 2009). Thus, following the recommendation of Product Environmental Footprint Guide (EC-JRC, 2017), this study assessed the base case and alternative scenarios, excluding long-term emissions (sections 5.1 and 5.2) and, performed this sensitivity analysis, including them. It is important to note that the results obtained by Impact

2002+ are not affected by long-term emissions, therefore, only the results obtained by CML baseline are presented in this section.

Table 74 lists the characterised and normalised results obtained by using the CML baseline v3.03 methodology including long-term emissions, and the contributions of each impact category with reference to the total impact after normalisation. The results show that "Marine Aquatic Ecotoxicity" and "Fresh Water Aquatic Ecotoxicity" are the most important impact categories, accounting for over 90% of the total impacts.

Table 74. Environmental profile of C&DW management system related to the functional unit, in the base case scenario. Data obtained by CML baseline (including long-term emissions).

Impact category	Characterisation		Normalisation (World)	Contribution (based on normalisation)
Marine aquatic ecot.	**2.90E+08**	**kg 1,4-DB eq**	**1.50E-06**	**86.22%**
Fresh water aquatic ecot.	**3.87E+05**	**kg 1,4-DB eq**	**1.64E-07**	**9.44%**
Human toxicity	1.18E+05	kg 1,4-DB eq	4.58E-08	2.64%
Terrestrial ecotoxicity	1.14E+04	kg 1,4-DB eq	1.04E-08	0.60%
Abiotic depletion (fossil fuels)	-2.00E+06	MJ	-5.25E-09	0.30%
Acidification	-8.55E+02	kg SO_2 eq	-3.58E-09	0.21%
Eutrophication	5.32E+02	kg PO_4^{3-} eq	3.36E-09	0.19%
Photochemical oxidation	-1.14E+02	kg C_2H_4 eq	-3.11E-09	0.18%
Global warming	-9.82E+04	kg CO_2 eq	-2.35E-09	0.14%
Abiotic depletion	3.03E-01	kg Sb eq	1.45E-09	0.08%
Ozone layer depletion	2.16E-03	kg CFC-11 eq	9.52E-12	0.001%

Table 75 presents the contribution of the stages for each impact category. The values in bold represent the most significant stages that together contribute over 80% to a specific impact category. The highlighted values represent the avoided impacts showed in Figure 69.

Figure 69. Environmental impact contribution of the main stages related to C&DW management system in the base case scenario (in percentages of the total impact). Data obtained by CML baseline (including long-term emissions).

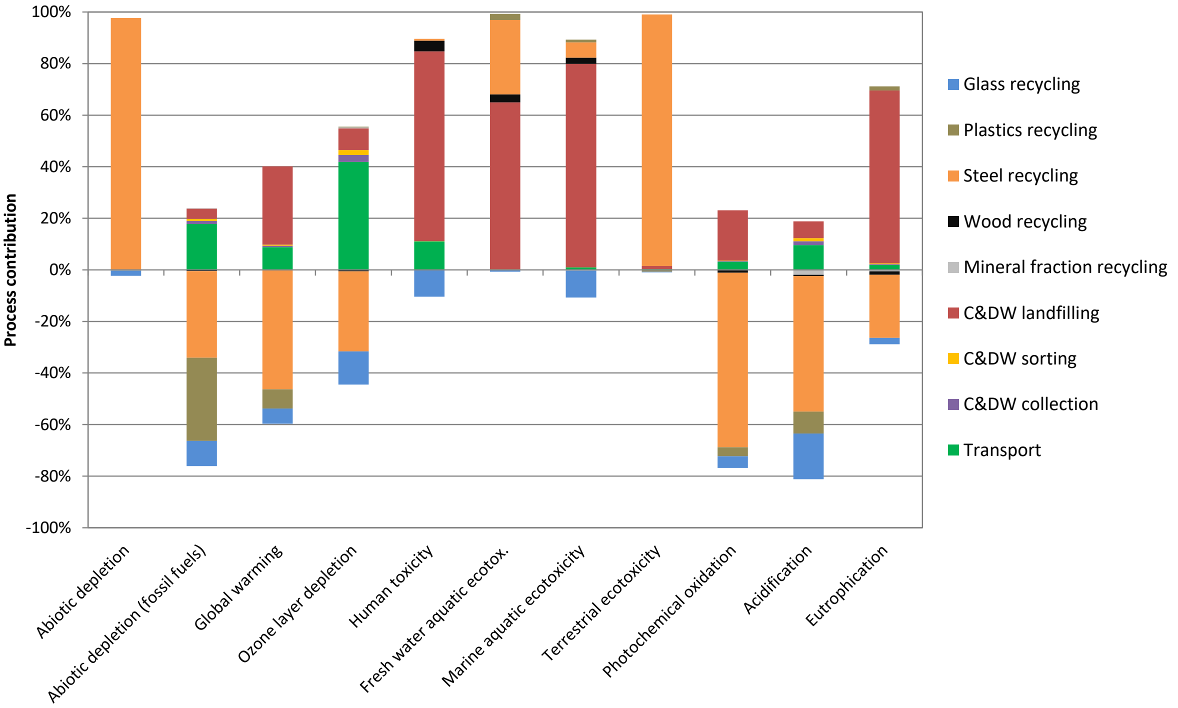


Table 75. Contribution percentage of the main stages related to C&DW management system in the base case scenario. The values in bold represent the most significant stages that together contribute over 80% to a specific impact category and the values highlighted in grey indicate avoided impacts. Data obtained by CML baseline (including long-term emissions).

Impact category	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling	Total
Abiotic depletion	0.11%	0.00%	0.00%	0.03%	0.03%	0.03%	**97.52%**	0.28%	1.99%	**97.52%**
Abiotic depletion (fossil fuels)	**17.81%**	1.14%	0.83%	3.98%	0.16%	0.47%	**33.59%**	**32.32%**	9.70%	**83.72%**
Global warming	**8.83%**	0.55%	0.40%	**30.45%**	0.08%	0.25%	**46.10%**	7.43%	5.92%	**85.38%**
Ozone layer depletion	**41.83%**	2.70%	1.95%	8.40%	0.37%	0.60%	**31.02%**	0.24%	**12.89%**	**85.73%**
Human toxicity	**11.03%**	0.09%	0.07%	**73.59%**	0.07%	4.13%	0.71%	0.02%	**10.29%**	**94.91%**
Fresh water aquatic ecotoxicity	0.20%	0.01%	0.00%	**64.74%**	0.01%	3.13%	**28.82%**	2.37%	0.71%	**93.56%**
Marine aquatic ecotoxicity	0.95%	0.03%	0.02%	**78.92%**	0.29%	2.34%	**6.01%**	1.01%	**10.41%**	**95.35%**
Terrestrial ecotoxicity	0.34%	0.00%	0.00%	1.14%	0.00%	0.10%	**97.59%**	0.61%	0.21%	**97.59%**
Photochemical oxidation	3.15%	0.24%	0.17%	**19.57%**	0.01%	1.12%	**67.67%**	3.50%	4.56%	**87.24%**
Acidification	**9.59%**	1.55%	1.12%	6.55%	1.89%	0.49%	**52.61%**	**8.50%**	**17.70%**	**88.40%**
Eutrophication	1.88%	0.38%	0.27%	**67.03%**	0.57%	1.37%	**24.42%**	1.64%	2.44%	**91.45%**

After the inclusion of long-term emissions, the characterised results of "Human Toxicity", "Fresh Water Aquatic Ecotoxicity" and "Marine Aquatic Ecotoxicty" reveal the C&DW landfilling as the main important stage. These results are different if compared to those obtained by excluding the long-term emissions (see Figure 58), where steel recycling provides significant avoided impacts for "Human Toxicity" and "Marine Aquatic Ecotoxicity" and, impacts of transport are the most important for "Human Toxicity".

Figure 70 presents the normalised results which confirm C&DW landfilling as the main contributor for the generated impacts, and reveal that only glass recycling has a significant contribution for the avoided impacts. The contribution analysis of "Marine Aquatic Ecotoxicity" (Figure 71) shows that the emissions of vanadium, beryllium and nickel into water comes from long-term leachate, mainly caused by paperboard and plastics wastes.

There is an important difference related to the impacts of steel recycling. The previous results (without long-term emissions) present a significant avoided impacts due to steel recycling (see Figure 59), while in this sensitivity analysis results (Figure 70) steel recycling provides generated impacts. The contribution analysis (Figure 71) show that the impacts are related to the emission of vanadium into water due to the landfilling of the slag and dust produced in the EAF process.

Figure 70. Normalised results of impact assessment related to the C&DW management system in the base case scenario, obtained by using normalised factors for World (2000) of CML baseline methodology (including long-term emissions).

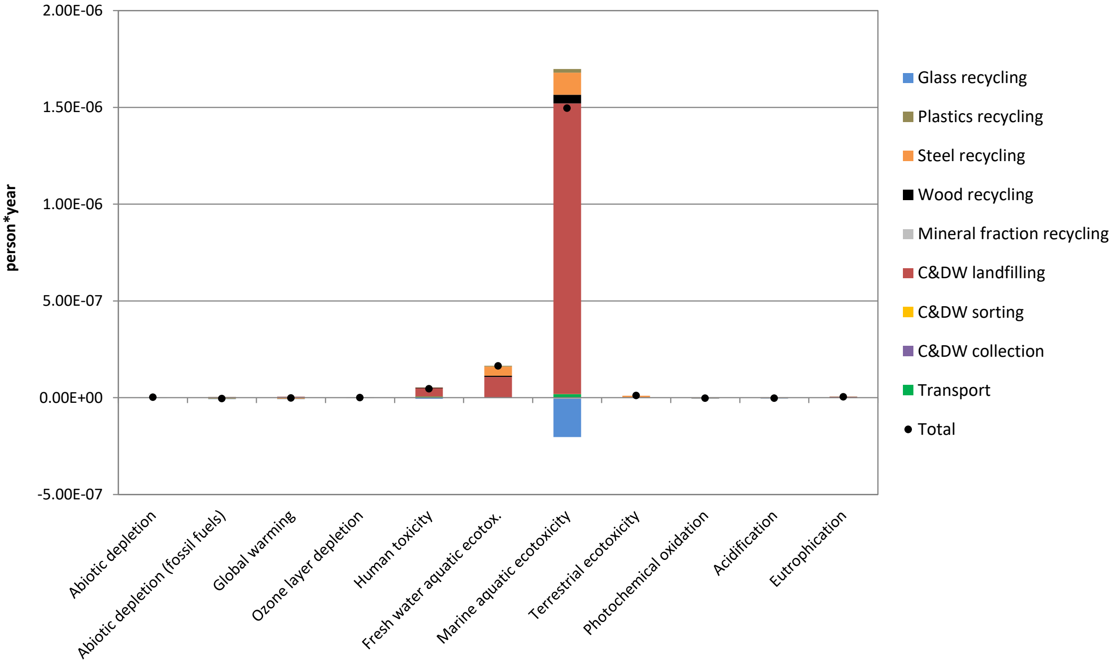
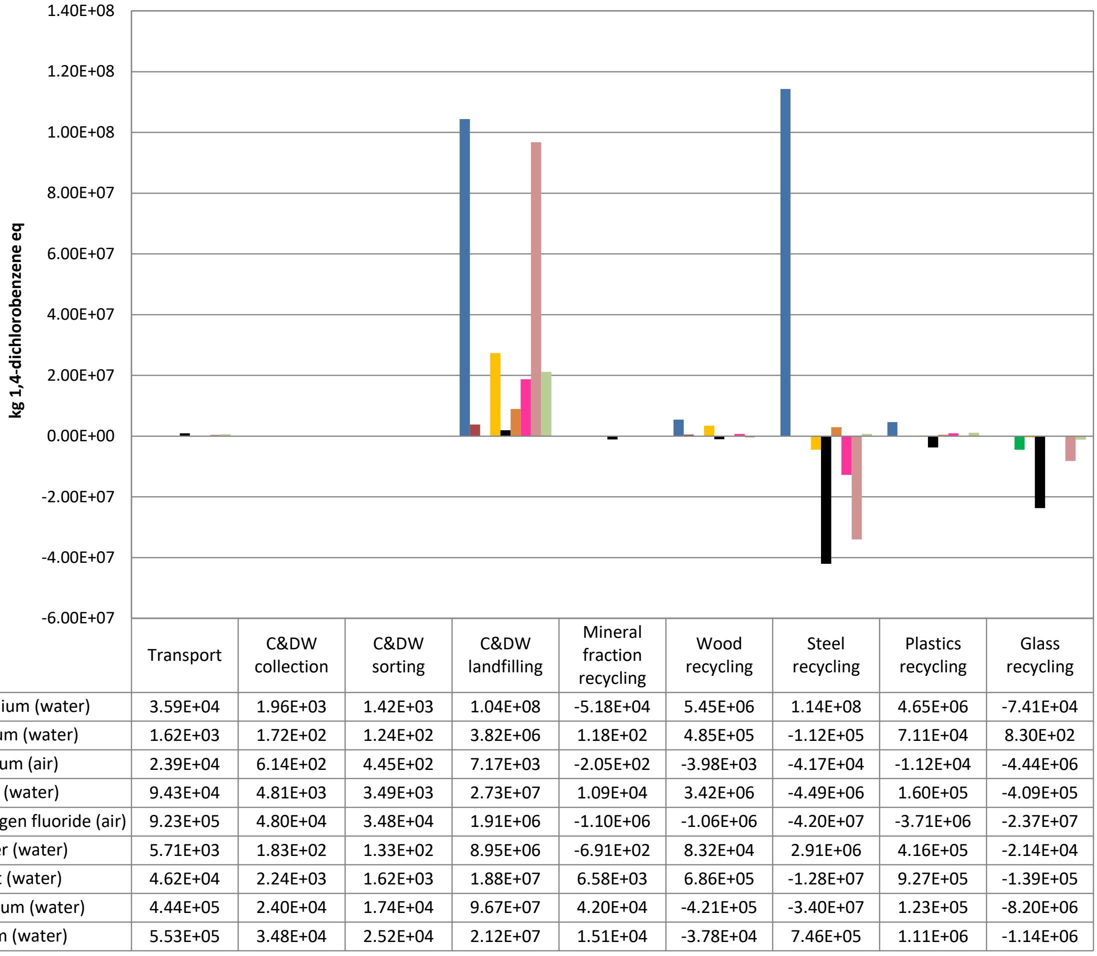


Figure 71. Contribution analysis for the impact category “Marine Aquatic Ecotoxicity” for the C&DW management system in the base case scenario (including long term-emissions).



	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
■ Vanadium (water)	3.59E+04	1.96E+03	1.42E+03	1.04E+08	-5.18E+04	5.45E+06	1.14E+08	4.65E+06	-7.41E+04
■ Thallium (water)	1.62E+03	1.72E+02	1.24E+02	3.82E+06	1.18E+02	4.85E+05	-1.12E+05	7.11E+04	8.30E+02
■ Selenium (air)	2.39E+04	6.14E+02	4.45E+02	7.17E+03	-2.05E+02	-3.98E+03	-4.17E+04	-1.12E+04	-4.44E+06
■ Nickel (water)	9.43E+04	4.81E+03	3.49E+03	2.73E+07	1.09E+04	3.42E+06	-4.49E+06	1.60E+05	-4.09E+05
■ Hydrogen fluoride (air)	9.23E+05	4.80E+04	3.48E+04	1.91E+06	-1.10E+06	-1.06E+06	-4.20E+07	-3.71E+06	-2.37E+07
■ Copper (water)	5.71E+03	1.83E+02	1.33E+02	8.95E+06	-6.91E+02	8.32E+04	2.91E+06	4.16E+05	-2.14E+04
■ Cobalt (water)	4.62E+04	2.24E+03	1.62E+03	1.88E+07	6.58E+03	6.86E+05	-1.28E+07	9.27E+05	-1.39E+05
■ Beryllium (water)	4.44E+05	2.40E+04	1.74E+04	9.67E+07	4.20E+04	-4.21E+05	-3.40E+07	1.23E+05	-8.20E+06
■ Barium (water)	5.53E+05	3.48E+04	2.52E+04	2.12E+07	1.51E+04	-3.78E+04	7.46E+05	1.11E+06	-1.14E+06

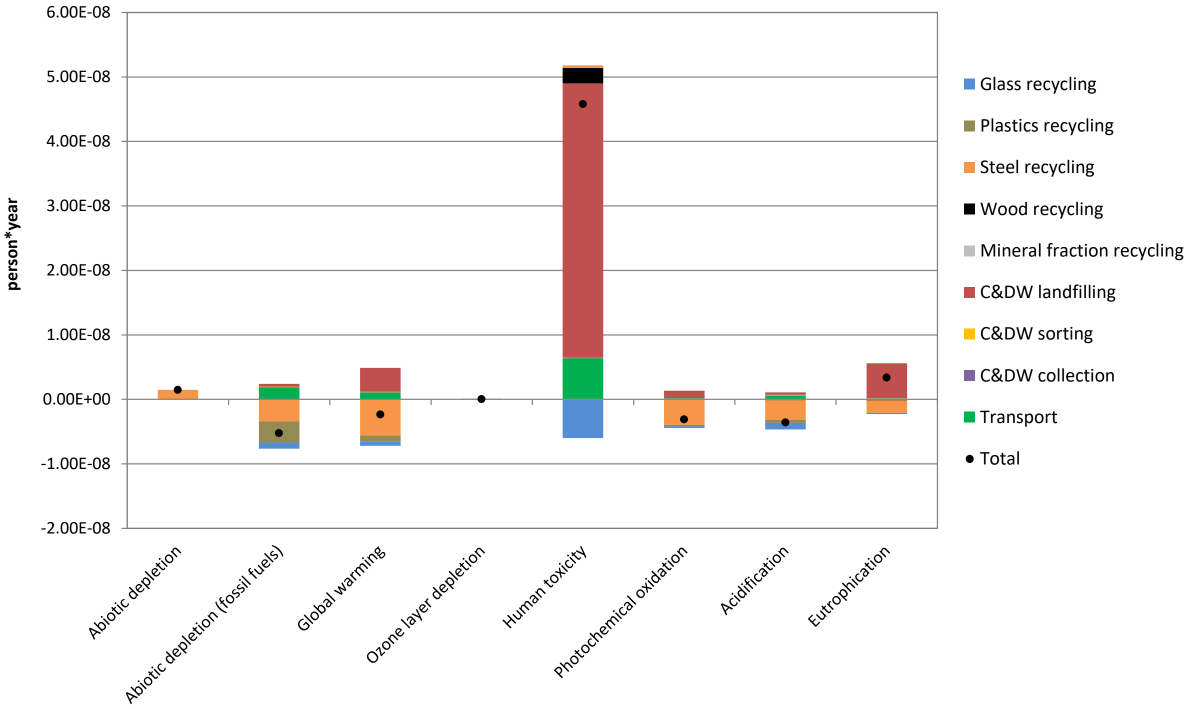
Table 76 presents the results after the exclusion of the ecotoxicity impact categories, following the same criteria used in the LCIA of base case and alternative scenarios. “Human Toxicity” account for 71% of total impacts, while in the previous results this category account for 44% (see Table 56). In addition, there is a slightly change in the ranking of the impact categories, including “Eutrophication” among the selected impact categories.

Table 76. Environmental profile of C&DW management system related to the functional unit, in the base case scenario. Excluding "Marine Aquatic Ecotoxicity", "Fresh Water Aquatic Ecotoxicity" and "Terrestrial Ecotoxicity" categories. Data obtained by CML baseline (including long-term emissions).

Impact category	Characterisation		Normalisation (World)	Contribution (based on normalisation)
Human toxicity	**1.18E+05**	**kg 1,4-DB eq**	**4.58E-08**	**70.56%**
Abiotic depletion (fossil fuels)	**-2.00E+06**	**MJ**	**-5.25E-09**	**8.09%**
Acidification	**-8.55E+02**	**kg SO_2 eq**	**-3.58E-09**	**5.52%**
Eutrophication	**5.37E+02**	**kg PO_4^{3-} eq**	**3.39E-09**	**5.18%**
Photochemical oxidation	**-1.14E+02**	**kg C_2H_4 eq**	**-3.11E-09**	**4.79%**
Global warming	**-9.71E+04**	**kg CO_2 eq**	**-2.32E-09**	**3.62%**
Abiotic depletion	3.03E-01	kg Sb eq	1.45E-09	2.23%
Ozone layer depletion	2.16E-03	kg CFC-11 eq	9.54E-12	0.01%

Normalised results (Figure 72) still confirm the C&DW landfilling as the main contributor to the generated impacts, followed by transport. Unlike the previous results (Figure 70), steel recycling is decisive to the avoided impacts.

Figure 72. Normalised results of impact assessment related to the C&DW management system in the base case scenario, obtained by using normalised factors for World (2000) of CML baseline methodology (including long-term emissions). Excluding "Marine Aquatic Ecotoxicity", "Fresh Water Aquatic Ecotoxicity" and "Terrestrial Ecotoxicity" categories.



The contribution analysis for the impact categories listed in Table 83 are available in Appendix 8 (Figures A8.1 to A8.6), and Table 77 supports the analysis of data obtained from the contribution analysis. “Abiotic Depletion” and “Ozone Layer Depletion” categories were not included in the contribution analysis due to their negligible contribution to the total impacts.

Among the selected impact categories, differences have been noticed only in the results of “Human Toxicity”. The previous results have pointed out the transport as the most important stage for the generated impacts, while in the sensitivity analysis, impacts from C&DW landfilling are the most important, due to emissions into groundwater of vanadium and thallium, from short- and long-term leachate of plastics wastes, which are also related to the impacts of “Eutrophication”.

Figure 73 presents the normalised results considering the three main stages of the C&DW management system, according to the selected impact categories of CML baseline. The comparison with the results obtained by Impact 2002+ (see Figure 64) shows again a fair similarity between the results related to the following groups of impact categories: “Abiotic Depletion (fossil fuels)” and “Non-Renewable Energy”; “Global Warming”; “Acidification” and “Respiratory Inorganics”. However, the results of “Human Toxicity” of CML baseline and “Human Toxicity” (“Carcinogens” and “Non-Carcinogens”) of Impact 2002+ are not directly comparable. Moreover, it should be noted a limited, but not negligible, value of “Eutrophication” by using CML methodology, which is instead almost nugatory by using Impact 2002+.

Table 77. Main data obtained from contribution analysis of life cycle impact assessment results acquired by CML baseline (including long-term emissions).

Impact categories	**Important stages**	**Important elementary flows**	**Important processes**
Human toxicity	Glass recycling (-)	Selenium	Primary glass production (without cullets)
	C&DW landfilling (+)	Thallium Vanadium	Plastics wastes landfilling
	Transport (+)	Antimony	Brake wear emissions (lorry)
Abiotic depletion (fossil fuels)	Steel recycling (-)	Hard coal	Hard coal mine operation
	Plastics recycling (-)	Crude oil Natural gas	PVC suspension polymerised and HDPE granulate production
	Transport (+)	Crude oil	Petroleum production
Acidification	Steel recycling (-)	Sulphur dioxide	Sinter iron production
	Glass recycling (-)	Sulphur dioxide	Primary glass production (without cullets)
	Plastics recycling (-)	Sulphur dioxide	PVC suspension polymerised and HDPE granulate production
	Transport (+)	Nitrogen oxides	Transport, lorry 16-32 metric ton (EURO4)
		Sulphur dioxide	Petroleum refinery operation
Eutrophication	Steel recycling (-)	Phosphate	Spoil from hard coal mining leachate
	C&DW landfilling (+)	Chemical oxygen demand	Plastics wastes landfilling
Photochemical oxidation	Steel recycling (-)	Carbon monoxide (fossil)	Sinter iron production
	C&DW landfilling (+)	Methane (biogenic)	Paperboard waste landfilling
Global warming	Steel recycling (-)	Carbon dioxide (fossil)	Pig iron production
	C&DW landfilling (+)	Methane (biogenic)	Paperboard waste landfilling
	Transport (+)	Carbon dioxide (fossil)	Transport, lorry 16-32 metric ton (EURO4)

Legend

(+) Environmental impact (-) Avoided environmental impact
🟦 Emission into air 🟧 Emission into soil 🟩 Emission into water 🟨 Raw material

Figure 73. Normalised results of impact assessment for the three main stages of C&DW management system in the base case scenario, obtained by using normalised factors for World of CML baseline methodology (including long-term emissions).

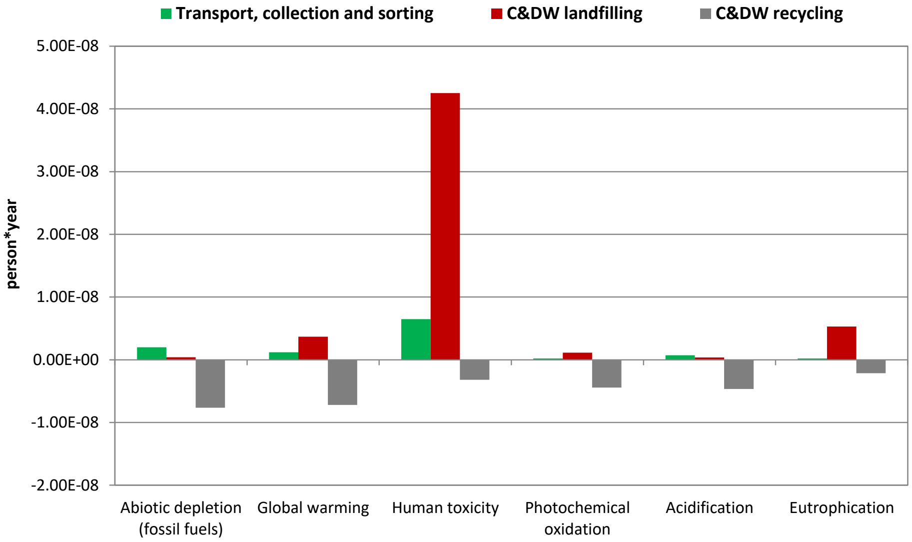
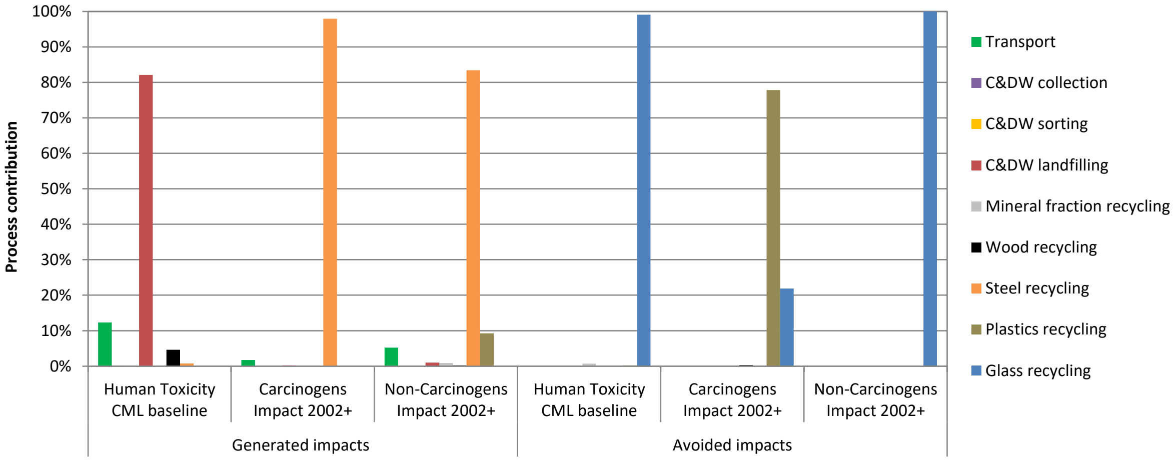


Figure 74 allows to analyse the results of "Human Toxicity" (with long-term emissions), "Carcinogens" and "Non-Carcinogens" in detail. Unlike the results showed in Figure 68, C&DW landfilling is the most important stage for the generated impacts of "Human Toxicity", because the influence of long-term emissions from landfills is highly emphasised in CML baseline. In contrast, these emissions do not appear so important for Impact 2002+, which uses different characterisation models for toxicity categories. In the previous results (Figure 68), steel recycling represents 65% of the avoided impacts for "Human Toxicity", and when long-term emissions are considered, it represents only 0.71% of the generated impacts.

Figure 74. Percentage contribution of each management stage to the generated and/or to the avoided impacts for "Human Toxicity", "Carcinogens" and "Non-Carcinogens". Data related to the characterisation analyses of base case scenario (including long-term emissions).



5.5 DISCUSSION

The results obtained by the LCA study indicate steel recycling as crucial for the avoided impacts of the C&DW management system, since it is the main contributor for "Global Warming" (77%), "Acidification" (65%) and "Respiratory Inorganics" (82%). LCA studies about end-of-life phase of residential buildings reported the same importance of steel recycling for the avoided impacts of the C&DW management (BLENGINI, 2009; VITALE *et al.*, 2017). Iron and steel represents only 3.2% of the C&DW composition, but its role in the overall environmental performance of the management system is crucial.

Although the avoided impacts resulting from glass and plastics recycling are lower compared to those of steel recycling, these fractions cannot be neglected. Glass recycling contributes to the avoided impacts of "Human Toxicity" (29%), "Acidification" (22%), "Non-Carcinogens" (51%) and "Respiratory Inorganics" (11%). In this study, it was assumed that recycled glass (glass cullet) can be used as raw material in the glass package production, with the substitution ratio of 1:0.82 (CREMIATO *et al.*, 2017), i.e. 1 tonne of recycled glass substitutes 0.82 tonne of primary glass. In addition, it has been considered that the recycled glass substitutes 55% of primary glass and 45% of secondary glass (CEMPRE, 2011), following the approach proposed by Gala *et al.* (2015).

In practice, glass scraps from construction and demolition activities are not recycled in the same process than the scraps from glass packages (bottles, jars, etc.), as assumed in this study due to the absence of data. Thus, a detailed study about the recycling potential of glass from the construction industry is necessary, including accurate data gathering on the current recycling process and recycling rates, as well as the avoided product and its substitution factor.

In accordance with Prestes *et al.* (2012), the composition of plastics was adopted as PVC (52%), HDPE (29%), PET (11%) and PP (8%), whose recycling contributes mainly to the avoided impacts of "Abiotic Depletion (fossil fuels)" (42%), "Acidification" (65%), "Carcinogens" (78%) and "Non-Renewable Energy" (46%). In this case, there are limitations related to data quality, since the LCI of the recycling processes and avoided products (virgin resins) were obtained from literature (YE *et al.*, 2017; PERUGINI; MASTELLONE; ARENA, 2005) and Ecoinvent v3.1 (2014) database (both updated with Brazilian energy mix), due to the lack of availability of local data.

The recycled plastics have application in the industry, replacing their virgin resins; however, in some cases, the recycled plastics are applied in low value products. For that, it was assumed the substitution factor of 1:0.81 (RIGAMONTI; GROSSO; SUNSERI, 2009), in order to reflect the loss of quality of recycled vs. virgin resins. Although this factor has been used by LCA studies on C&DW management (MERCANTE *et al*., 2012; HOUSSAIN; WO; POON, 2017), it does not seem the most appropriate, because it was defined based on market price of granules of recycled plastics in relation to virgin resins. Gala *et al*. (2015) have identified a demand for studies comparing the properties of recycled vs. primary materials, especially in the case of plastics.

Wood recycling provides minor avoided impacts for all selected categories (less than 3%), with exception of “Non-Carcinogens”. Usually, the wood wastes from construction sites are mixed with other materials (such as concrete, mortar, metals), therefore, it was assumed that 30% of wood wastes are sent to landfills, based on the study of Costa (2009). In this sense, better management practices both at construction sites (through source segregation) and recycling facilities (by increasing the process efficiency), could improve the quality of wood wastes, and consequently, provide larger environmental benefits.

Although the mineral fraction accounts for approximately 87% of C&DW, the results pointed out that its impacts are insignificant. Considering the selected municipalities, 15% of the mineral fraction is recycled, 25% landfilled and 60% stored for future use. The avoided impacts of recycling represent less than 2% for the selected impact categories and, the alternative scenarios showed that the increase of recycling rates only improve the results for the categories “Acidification” and “Respiratory Inorganics”.

It is important to highlight that this type of mineral, such as soil, gravel and sand, are not considered in the impact categories of “Abiotic Depletion” of CML baseline and “Mineral Extraction” of Impact 2002+. In this context, Borghi, Pantini and Rigamonti (2018) have adopted an indicator in order to quantify the non-renewable virgin and raw material consumption, expressed in terms of kg of sand and gravel consumed or saved. Moreover, Vitale *et al*. (2017) mentioned that the small contribution of mineral fraction recycling cannot be neglected, since it has been highlighted in terms of land occupation due to the avoided landfilling; however, further studies should be carried out to investigate the role of mineral fraction recycling in a life cycle perspective.

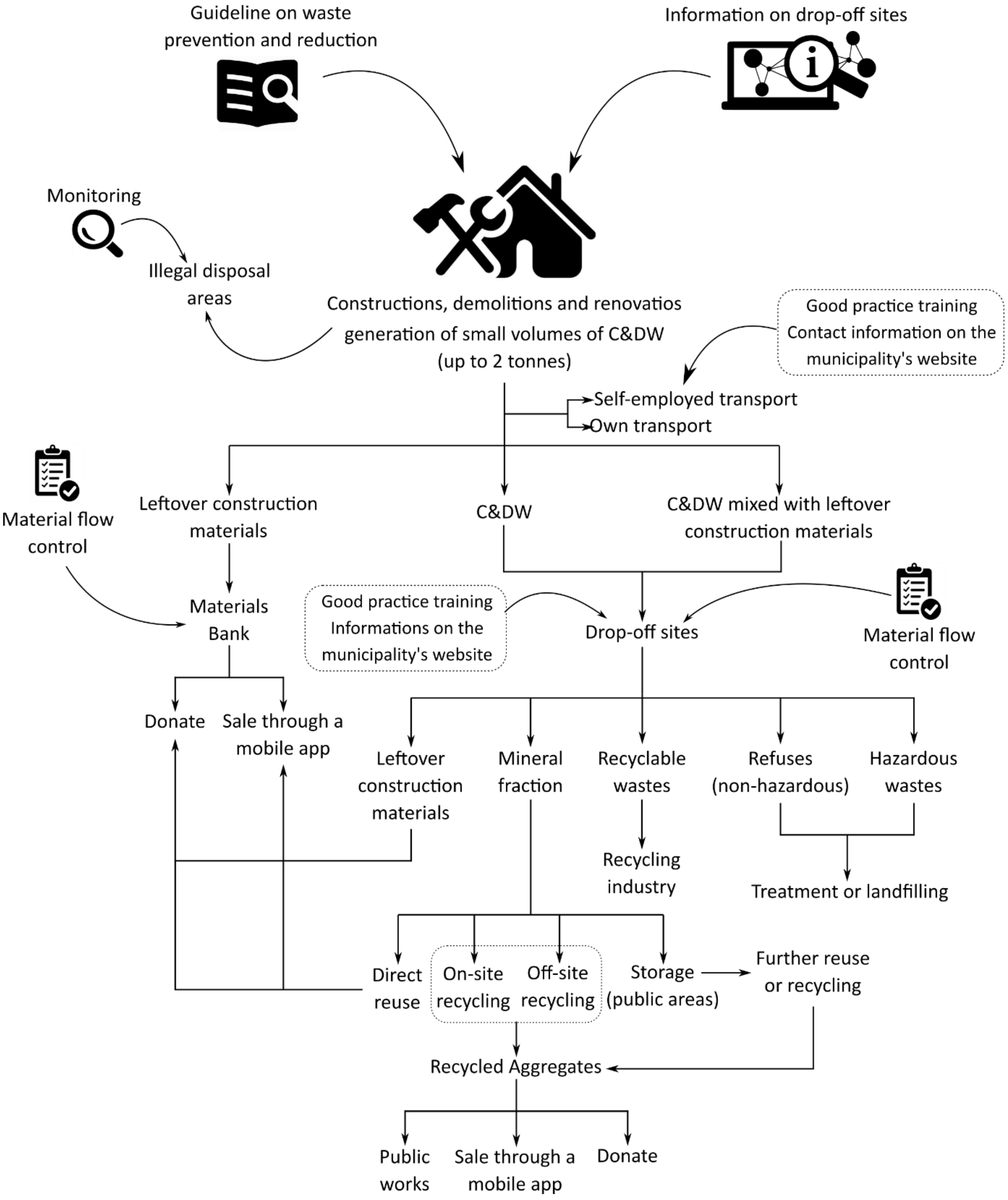
The mineral fraction represents 73% of the C&DW landfilled, and the impacts refer to diesel and other materials consumptions required to the landfill operation. Then, mineral fraction landfilling has the largest contribution for “Abiotic Depletion (fossil fuels)”, “Acidification”, “Respiratory Inorganics” and “Non-Renewable Energy”, mainly due to diesel emissions. In accordance with Bovea and Powell (2016), future LCI models for inert landfilling should include leachate or gas emissions, since small amounts of biodegradable materials (wood, painted wood, paper/cardboard, etc.) can be disposed into landfills. Some studies have pointed out the impacts of leachate from C&DW landfilling (ENGELSEN *et al.*, 2010; BUTERA; CHRISTENSEN; ASTRUP, 2014; CÓRDOBA; SCHALCH, 2015); on the other hand, current studies (HOUSSAIN; WU; POON, 2017; DI MARIA; EYCKMANS; ACKER, 2018; BORGHI; PANTINI; RIGAMONTI, 2018) have not considered this issue. In future studies, it would be interesting include this type of data, since the presence of unsorted waste mixed with the mineral fraction is disposed into inert landfills. Regarding to the mineral fraction stored, there is a consensus of not considering the environmental burdens about this stage, but it is very important to assure that this fraction remains stored during a short period of time, avoiding the creation of illegal landfills.

As highlighted in several studies (see section 3.3), transport is one of the most important stages in the C&DW management, due to the large volumes of waste transported and transport distances. In this study, the C&DW transport from the generator to sorting areas (tu_2) and mineral fraction transport from sorting areas to recycling facilities (tu_6) are the main responsible for the impacts of C&DW transport. The largest impacts of both cases are related to the high amount of waste transported (6,910 and 6,475 tonnes, respectively), and not to the distance (90 km and 48 km, respectively). The installation of new sorting areas could reduce the transport distance (tu_2) and reduce the illegal disposal. An alternative to reduce the transport distance of mineral fraction from sorting areas to recycling facilities is the use of small mobile facilities, which would be shared among some sorting areas. That would be especially helpful for the municipality of Campinas, due to its large size.

The sensitivity analysis related to the variations of the C&DW composition reveals the main fractions that may significantly affect the results, such as gypsum (if it is sent to sanitary landfills), steel, glass, plastics and paperboard. This suggests that the control of the waste stream is fundamental to determine the environmental profile of the C&DW management system.

Finally, based on the literature review, visits on the C&DW management infrastructures, interviews with the responsible for the C&DW management of the municipalities from PCJ Watershed and, results of the LCA study, a set of recommendations of potential improvements on the management system of the C&DW from small generators is summarized in Figure 75, and discussed below.

Figure 75. Proposed management system for the C&DW from small generators.



In order to reduce or eliminate the illegal disposal of C&DW, the municipalities could implement routines for registration and monitoring of irregular disposal areas, with the support of tools, such as the Geographic Information System (GIS). The municipal departments responsible for the C&DW management could issue warnings and fines, and disseminate these occurrences in local media and social networks to raise public awareness. In addition, the municipalities should create systematic awareness programs about environmental and socioeconomic impacts from C&DW illegal disposal, along with the dissemination of the available alternatives for the proper C&DW management.

The sorting areas or drop-off sites are an important alternative to manage the C&DW from small generators. In this sense, it is suggested the analysis of demand of new drop-off sites along with the study on the coverage of the existing drop-off sites, with the support of tools, such as GIS and Google Earth. In order to ensure the proper utilisation of these areas, it is essential to provide information about the drop-off sites operation on the municipality's website, local media and social networks.

The sorting areas must comprise a material flow control (generation source, waste composition and quantity); employees training about the waste sorting; proper containers with clear identification to ensure the effective waste sorting; storage site or container for materials that can be reused (leftover materials). Moreover, these areas must be monitored by the public authorities and environmental agencies.

During the technical visits in the sorting areas of the selected municipalities, it was observed a considerable amount of materials with potential to reuse. Thus, the municipalities could develop a mobile app to sale the materials that can be reused, with the information of the material type (composition), quantity and drop-off site location.

The mineral fraction represents the large portion of the C&DW, with high potential to reuse or recycle. In this context, the municipalities must provide areas for temporary storage, organizing the mineral fraction according to their further application (direct reuse or recycling) and types (red fraction – ceramic materials; grey fraction – concrete materials and mixed fraction), and keeping a record on the amount of stored material.

Regarding to the mineral fraction recycling , it is important the analysis on the economic feasibility of installing a stationary recycling facility in the municipality, considering the C&DW generation and demand for recycled aggregates; and, the analysis of the possible use of a shared mobile recycling facility with other municipalities. Considering that most of the Brazilian municipalities are small sized, it is recommended to encourage the public-private partnerships and/or intermunicipal consortia for the operation of recycling facilities.

Regardless of the existence of a recycling facility, the municipalities could elaborate laws/decrees on the mandatory use of a certain percentage of recycled aggregates in public and private works, and provide technical capacitation about the applications of the recycled aggregates.

Usually, the transport of C&DW from small generator can also be carried out by self-employed, which must be registrated and receive training on good environmental practice. In addition, the contact of the self-employed transport who received training could be available on the municipality’s website.

Finally, it is fundamental the development of guidelines on C&DW prevention and minimisation focused on small construction, demolition and renovation works. A potential initiative could be the creation of a materials bank to receive leftovers construction materials to donation to low-income families or sale through a mobile app.

CHAPTER

6

CONCLUSIONS

The potential environmental impacts of the C&DW management of thirteen representative municipalities located in the Piracicaba, Capivari and Jundiaí Watershed (São Paulo State, Brazil) were evaluated by means of an attributional LCA, taking into account two LCIA methodologies: CML baseline and Impact 2002+.

The results obtained by CML baseline indicate that “Human Toxicity” was the most important category, where the avoided impacts of steel recycling and the impacts generated by the transport were the main contributors. The results obtained by Impact 2002+ indicate that “Respiratory Inorganics” and “Global Warming” were the most important categories, where the avoided impacts of steel recycling had a crucial role, along with the generated impacts of transport and landfilling.

In general, the results highlighted the importance of the avoided impacts from recovered materials, mainly those related to steel, glass and plastics recycling. In this sense, the municipalities should invest in programs to encourage the sorting at construction sites, improving the quality of the recovered materials and, increasing the recycling rates. Moreover, the sensitivity analysis of the variation of the C&DW composition indicated that the non-mineral fraction may significantly affect the results. In this sense, the control of the waste stream is fundamental to determine the environmental profile of the C&DW management system. In this sense, it is important that LCA studies of C&DW management avoid analyses focusing only in the mineral fraction, neglecting the presence of other materials.

Although the mineral fraction represents a large quantity of the C&DW, its recycling does not appear remarkable for the avoided impacts. Conversely, its contribution to the impacts of transport was significant, consuming 76% of the total crude oil used throughout the management system. In this context, it is important to develop studies determining the impacts of the scarcity of natural aggregates used in the construction sector, in order to reveal the benefits of the C&DW recycling.

The results of the alternative scenarios indicated that the increase of the mineral fraction recycling and the production of medium quality recycled aggregates improve significantly the impact categories of “Acidification” (CML baseline) and “Respiratory Inorganics” (Impact 2002+) with reference to the base case scenario. In addition, the sensitivity analysis confirm the environmental feasibility of the use of the recycling facilities currently in operation, instead of the disposal of the mineral fraction into inert landfills, despite the transport distances.

Finally, it is important to mention that the main limitation of this study is the absence of local data on the C&DW flow, specially the waste composition. This aspect was partially overcome by the sensitivity analysis performed. Moreover, another important limitation is the lack of inventories on recycling processes of plastics, glass and gypsum, based on the Brazilian context. Regardless of these aspects, considering the existence of few LCA studies about C&DW management at municipal level, the applied methodology can be used as a starting point for future studies, as well as supporting the decisions of public managers.

6.1 SUGGESTIONS FOR FUTURE RESEARCH

Based on the results of this research and the experience acquired during this PhD, further research may be suggested on the following topics:

- To obtain primary data for the life cycle inventory of the recycling processes of plastics, glass and gypsum. Moreover, there is a need for studies to determine the substitution factor (quality factor) of the recovered materials, as suggested by Gala, Raugei and Fullana-I-Palmer (2015).
- To determine how the recycled aggregates can complement natural aggregates in a sustainable approach, as evaluated by Blengini and Garbarino (2010) for a Italian region, by means of the Geographical Information System and Life Cycle Assessment. Despite the abundant availability of natural aggregates in Brazil , in some regions it is not possible to extract this raw material, increasing the transport distances. This further study could include the development of a methodology to determine the impacts of the scarcity of natural aggregates used in the construction sector along with the impacts of land use. In addition, it is important to analyse the emissions from transport according to the Brazilian context.

- To propose an experimental study to determine the quality factor of the mineral fraction in order to apply it in the methodology developed by Borghi, Pantini and Rigamonti (2018).
- To develop a LCI of inert landfilling with the inclusion of leachate emissions from C&DW, based on Brazilian studies, such as Lima and Cabral (2013) and Córdoba and Schalch (2015).
- To include prevention scenarios as a management alternative for the C&DW, since it is the highest priority according to the waste hierarchy and, there are a limited number of LCA studies on this topic.
- To propose a model to gather primary data from the environmental licensing processes (for exemple, from the SIGOR of São Paulo State) in order to improve the Brazilian LCI data and further LCA studies on C&DW management.

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APPENDIXES

APPENDIX A1 – LITERATURE REVIEW: CONSTUCTION AND DEMOLITION WASTE

This appendix reports additional information about the articles, theses and dissertations used in the Literature Review about C&DW management systems.

Table A1.1. Articles about construnction and demolition waste management systems in the international context (Part I).

Published in 2010

Title: Critical success factors for on-site sorting of construction waste: A China study
Authors: Jiayuan Wang, Hongping Yuan, Xiangping Kang and Weisheng Lu
Journal: Resources, Conservation and Recycling
Cited by 141 (Google Scholar, 8th October 2018) *Journal Impact:* 5.120 (JCR, 2017)

Published in 2011

Title: European legislation and implementation measures in the management of construction and demolition waste
Authors: Paola Villoria Sáez, Mercedes del Río Merino, César Porras Amores and Alicia de San Antonio González
Journal: The Open Construction and Building Technology Journal
Cited by 24 (Google Scholar, 8th October 2018) *Journal Impact:* not informed (JCR, 2017)

Published in 2012

Title: Off-site sorting of construction waste: What can we learn from Hong Kong?
Authors: Lu Weisheng and Yuan Hongping
Journal: Resources, Conservation and Recycling
Cited by 31 (Google Scholar, 14th November 2018) *Journal Impact:* 5.120 (JCR, 2017)

Published in 2013

Title: Construction waste management policies and their effectiveness in Hong Kong: A longitudinal review
Authors: Weisheng Lu and Vivian W. Y. Tam
Journal: Renewable and Sustainable Energy Reviews
Cited by 76 (Google Scholar, 8th October 2018) *Journal Impact:* 9.184 (JCR, 2017)

Title: The evolution of construction waste sorting on-site
Authors: Hongping Yuan, Weisheng Lu and Jane Jianli Hao
Journal: Renewable and Sustainable Energy Reviews
Cited by 52 (Google Scholar, 8th October 2018) *Journal Impact:* 9.184 (JCR, 2017)

Published in 2015

Title: Encouraging the environmentally sound management of C&D waste in China: An integrative review and research agenda
Authors: Huabo Duan, Jiayuan Wang and Qifei Huang
Journal: Renewable and Sustainable Energy Reviews
Cited by 25 (Google Scholar, 8th October 2018) *Journal Impact:* 9.184 (JCR, 2017)

Title: Construction and demolition waste management – a holistic evaluation of environmental performance
Authors: Helena Dahlbo, John Bachér, Katja Lähtinen, Timo Jouttijärvi, Pirke Suoheimo, Tuomas Mattila, Susanna Sironen, Tuuli Myllymaa and Kaarina Saramäki
Journal: Journal of Cleaner Production
Cited by 67 (Google Scholar, 8th October 2018) *Journal Impact:* 5.651 (JCR, 2017)

Table A1.1. Articles about construnction and demolition waste management systems in the international context (Part II).

Published in 2016

Title: Developing strategies for managing construction and demolition wastes in Malaysia based on the concept of circular economy

Authors: Mohd Reza Esa, Anthony Halog and Lucia Rigamonti

Journal: Journal of Material Cycles and Waste Management

Cited by 15 (Google Scholar, 8th October 2018) *Journal Impact:* 1.693 (JCR, 2017)

Title: Development of a hybrid model to predict construction and demolition waste: China as a case study

Authors: Yiliao Song, Yong Wanga, Feng Liu and Yixin Zhang

Journal: Waste Management

Cited by 4 (Google Scholar, 8th October 2018) *Journal Impact:* 4.723 (JCR, 2017)

Title: A review on adoption of novel techniques in construction waste management and policy

Authors: Usman Aminu Umar, Nasir Shafiq, Amirhossein Malakahmad, Muhd Fadhil Nuruddin and Mohd Faris Khamidi

Journal: Journal of Material Cycles and Waste Management

Cited by 7 (Google Scholar, 8th October 2018) *Journal Impact:* 1.693 (JCR, 2017)

Published in 2017

Title: An empirical study of perceptions towards construction and demolition waste recycling and reuse in China

Authors: Ruoyu Jin, Bo Li, Tongyu Zhou, Dariusz Wanatowski and Poorang Piroozfar

Journal: Resources, Conservation & Recycling

Cited by 25 (Google Scholar, 14th November 2018) *Journal Impact:* 5.120 (JCR, 2017)

Title: Barriers and countermeasures for managing construction and demolition waste: A case of Shenzhen in China

Author: Hongping Yuan

Journal: Journal of Cleaner Production

Cited by 11 (Google Scholar, 14th November 2018) *Journal Impact:* 5.651 (JCR, 2017)

Title: Characterizing the generation and flows of construction and demolition waste in China

Authors: Lina Zheng, Huanyu Wu, Hui Zhang, Huabo Duan, Jiayuan Wang, Weiping Jiang, Biqin Dong, Gang Liu, Jian Zuo and Qingbin Song

Journal: Construction and Building Materials

Cited by 22 (Google Scholar, 14th November 2018) *Journal Impact:* 3.485 (JCR, 2017)

Published in 2017

Title: Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills

Authors: Olugbenga O. Akinade, Lukumon O. Oyedele, Saheed O. Ajayi, Muhammad Bilal, Hafiz A. Alaka, Hakeem A. Owolabi, Sururah A. Bello, Babatunde E. Jaiyeoba, Kabir O. Kadiri

Journal: Waste Management

Cited by 19 (Google Scholar, 14th November 2018) *Journal Impact:* 4.723 (JCR, 2017)

Published in 2018

Title: Construction and demolition waste best management practice in Europe

Authors: José-Luis Gálvez-Martos, David Styles, Harald Schoenberger and Barbara Zeschmar-Lahl

Journal: Resources, Conservation & Recycling

Cited by 5 (Google Scholar, 14th November 2018) *Journal Impact:* 5.120 (JCR, 2017)

Table A1.1. Articles about construnction and demolition waste management systems in the international context (Part III).

Published in 2018

Title: Construction and demolition waste management in China through the 3R principle
Authors: Beijia Huang, Xiangyu Wanga, Harnwei Kua, Yong Geng, Raimund Bleischwitz and Jingzheng Ren
Journal: Resources, Conservation & Recycling
Cited by 17 (Google Scholar, 14th November 2018) *Journal Impact:* 5.120 (JCR, 2017)

Title: Evaluating the transition towards cleaner production in the construction and demolition sector of China: A review
Authors: Patrizia Ghisellini, Xi Ji, Gengyuan Liu and Sergio Ulgiati
Journal: Journal of Cleaner Production
Cited by 2 (Google Scholar, 8th October 2018) *Journal Impact:* 5.651 (JCR, 2017)

Table A1.2. Articles on construnction and demolition waste management systems in the Brazilian context (Part I).

Published in 2010

Title: Gestão dos Resíduos de Construção e Demolição: Estudo da Situação no Município de São Carlos-SP, Brasil
Authors: José da Costa Marques Neto and Valdir Schalch
Journal: Engenharia Civil UM
Cited by 15 (Google Scholar, 18th October 2018) *Journal Impact:* not informed (JCR, 2017)

Published in 2011

Title: Diagnóstico da geração e da composição dos RCD de Fortaleza/CE
Authors: Maria Elane Dias de Oliveira, Raquel Jucá de Moraes Sales, Lúcia Andréa Sindeaux de Oliveira e Antonio Eduardo Bezerra Cabral
Journal: Engenharia Sanitária e Ambiental
Cited by 20 (Google Scholar, 18th October 2018) *Journal Impact:* 0.22 (JCR, 2017)

Published in 2012

Title: Cenário do Gerenciamento dos Resíduos da Construção e Demolição (RCD) em Uberaba-MG
Authors: Vinícius Arcanjo da Silva and André Luís Teixeira Fernandes
Journal: Sociedade & Natureza
Cited by 2 (Google Scholar, 18th November 2018) *Journal Impact:* not informed (JCR, 2017)

Title: Quantificação e classificação dos resíduos procedentes da construção civil e demolição no município de Pelotas, RS
Authors: Alessandra Buss Tessaro, Jocelito Saccol de Sá and Lucas Bastianello Scremin
Journal: Ambiente Construído
Cited by 39 (Google Scholar, 18th October 2018) *Journal Impact:* not informed (JCR, 2017)

Published in 2013

Title: Fatores críticos para a produção de agregado reciclado em usinas de reciclagem de RCC da região nordeste do Brasil
Authors: Adriana Virgínia Santana Melo, Emerson de Andrade Marques Ferreira and Dayana Bastos Costa
Journal: Ambiente Construído
Cited by 4 (Google Scholar, 18th October 2018) *Journal Impact:* not informed (JCR, 2017)

Title: Caracterização e classificação dos resíduos de construção civil da cidade de Fortaleza (CE)
Authors: Adriana Sampaio Lima and Antonio Eduardo Bezerra Cabral
Journal: Engenharia Sanitária e Ambiental
Cited by 16 (Google Scholar, 20th October 2018) *Journal Impact:* 0.22 (JCR, 2017)

Table A1.2. Articles sbout construnction and demolition waste management systems in the Brazilian context (Part II).

Published in 2015
Title: Modelo dinâmico de sistemas para o gerenciamento de resíduos da construção civil na cidade de Porto Alegre: estudo de caso
Authors: Luis Hernando Walteros Galarza, Sandra Tatiana Reyes Gómez, Estela Oliari Garcez, Érico Cunde Correa, Álvaro Chávez Porras and Isaac Huertas Forero
Journal: Engenharia Sanitária e Ambiental
Cited by 1 (Google Scholar, 18th October 2018) *Journal Impact:* 0.22 (JCR, 2017)
Title: Percepção da legislação ambiental, gestão e destinação final dos RCD – resíduos da construção e demolição: um estudo de caso em Parnamirim/RN/Brasil
Authors: Carlos Henrique Catunda Pinto, Alcimar Laurentino dos Santos and Ana Clea Marinho Miranda Catunda
Journal: Holos Environment
Cited by 3 (Google Scholar, 18th October 2018) *Journal Impact:* not informed (JCR, 2017)
Title: Estudo do potencial de contaminação de lixiviados gerados em aterros de resíduos da construção civil por meio de simulações em colunas de lixiviação
Authors: Rodrigo Eduardo Córdoba and Valdir Schalch
Journal: Engenharia Civil UM
Cited by 0 (Google Scholar, 20th October 2018) *Journal Impact:* not informed (JCR, 2017)
Published in 2016
Title: Forecasting of construction and demolition waste in Brazil
Authors: Diogo Henrique Fernandes Paz and Kalinny Patrícia Vaz Lafayette
Journal: Waste Management & Research
Cited by 9 (Google Scholar, 18th October 2018) *Journal Impact:* 1.90 (JCR, 2015)

Table A1.2. Articles about construnction and demolition waste management systems in the Brazilian context (Part III).

Published in 2018
Title: Uso de metodologia participativa na elaboração de Plano Municipal de Gestão de Resíduos da Construção Civil
Authors: Laís Peixoto Rosado and Carmenlucia Santos Giordano Penteado
Journal: Revsita DAE
Cited by 0 (Google Scholar, 18th November 2018) *Journal Impact:* not informed (JCR, 2017)
Title: Análise da eficiência dos Ecopontos a partir do georreferenciamento de áreas de disposição irregular de resíduos de construção e demolição
Authors: Laís Peixoto Rosado and Carmenlucia Santos Giordano Penteado
Journal: Sociedade & Natureza
Cited by 0 (Google Scholar, 18th November 2018) *Journal Impact:* not informed (JCR, 2017)

Table A1.3. Theses about C&DW management system in Brazil.

Author (year)	**Main objective**
Marques Neto (2009)	To study the current scenario of the C&DW management in the municipalities from Turvo Grande Watershed.
Buselli (2012)	To develop a detailed diagnosis of the C&DW management in Viçosa (Minas Gerais State), in order to propose a more consistent municipal management system. To evaluate the presence of trace metals in fine particulates of C&DW, considering their use in chemical barriers.
Pimentel (2013)	To estimate the amount of C&DW in João Pessoa (Paraíba State) by analysing the material flow from the generation to the C&DW Recycling Facility and estimating the fraction sent to illegal disposal areas.
Farias (2014)	To contribute to the municipal government by means of a proposal to implement a preventive C&DW management in Teresina (Piauí State).
Magagnin Filho (2016)	To analyse the C&DW recycling in Londrina (Paraná State), verifying the compliance with environmental requirements and, the existence of a procedure to identify contamination in the C&DW as well as in the recycled aggregates produced.
Amorin (2016)	To analyse the economic and environmental viability of the C&DW recycling performed by PROGUARU in Guarulhos (São Paulo State).

Table A1.4. Dissertations about C&DW management system in Brazil (Part I).

Author (year)	**Main objective**
Sapata (2002)	To propose an integrated C&DW management in Maringá (Paraná State).
Marques Neto (2003)	To analyse the current C&DW management in São Carlos (São Paulo State), through a qualitative and quantitative waste characterisation, analysis of the infrastructures used for the management, in order to provide strategies for an integrated C&DW management system, including recycling and reuse practices.
Rocha (2006)	To evaluate the current C&DW management, through a qualitative and quantitative characterisation by means of physical and microstructural tests, in order to determine the composition, granulometry, density and minerals present in the samples collected from work sites located in Brasília.
Silva (2006)	To study the environmental and business solutions implemented by the municipality of Jundiaí (São Paulo State), in its Solid Waste Management Centre - GERESOL, from the point of view of partnerships with the private sector.
Tavares (2007)	To analyse the C&DW management practices in Aracajú (Sergipe State) from interviews with actors involved in the management (public government, cooperatives, transporters, and consulting firms).
Ramos (2007)	To obtain quality indicators of the C&DW generated in the municipality of Vitória (Espírito Santo State) managed by the public government, in order to evaluate its potential as recycled aggregate for use in the construction industry.
Veiga (2008)	To identify the municipal experiences carried out in accordance with the C&DW legislation and standards, by means of case studies focused on the management in Belo Horizonte (Minas Gerais State) and São José do Rio Preto (São Paulo State).
Ribeiro (2008)	To conduct an analysis on the C&DW management of the metropolitan region of São Paulo, based on information provided by the involved agents and visits to storage, sorting, recycling and final disposal sites.
Santos (2008)	To identify the materials generated by ten construction companies and the environmental impacts of eleven illegal disposal areas, in order to analyse the potential of reuse of these materials.

Table A1.4. Dissertations about C&DW management system in Brazil (Part II).

Author (year)	Main objective
Lucero (2008)	To analyse the corrective approach adopted by the C&DW management system, its particularities and difficulties, and the current scenario of the C&DW recycling in Rio de Janeiro.
Wiens (2008)	To analyse the C&DW management of the five largest municipalities of the Tietê-Jacaré Watershed.
Simões (2009)	To determine the efficiency of the drop-off sites in Belo Horizonte (Minas Gerais State) in relation to its main users, and propose improvements.
Ferreira (2009)	To analyse the C&DW management in Brasília, with emphasis on the influence of the life cycle thinking.
Rios (2009)	To analyse the socioenvironmental and economic implications caused by the C&DW in Fortaleza (Ceará State).
Uwai (2009)	To propose a method for the planning and management of processes and costs of alternative C&DW drop-off sites.
Brönstrup (2010)	To present guidelines for the development of a C&DW management system for the municipality of Gramado (Rio Grande do Sul State), in accordance with CONAMA Resolution nº 307/2002, from the perspective of the public authority.
Córdoba (2010)	To study the integrated C&DW management system of São Carlos (São Paulo State) and develop indexes for management strategies elaboration, through quantitative and qualitative characterisation.
Silva (2010)	To study the current C&DW management in Taubaté (São Paulo State), based on the CONAMA Resolution nº 307/2002, in order to provide alternatives for the management system.
Inojosa (2010)	To elaborate a timeline on the C&DW management in Brasilia, through a literature review and interviews.
Melendres (2011)	To analyse the concept of integrated C&DW management in accordance with the CONAMA Resolution nº 307/2002 and discuss how this concept was applied in Uberlândia (Minas Gerais State) between 2003 and 2010.
Prata (2013)	To propose a management model to minimize the current problems associated with the C&DW management in the urban area of Lagarto (Sergipe State).
Lúcio (2013)	To study the current situation and the evolution of the integrated C&DW management system in Belo Horizonte (Minas Gerais State), by analysing local basic indicators, C&DW generation and public equipment used in the management.
Dondo (2014)	To evaluate the C&DW management in Cuiabá and Várzea Grande (Mato Grosso State) and propose improvements for the management.
Barreto (2014)	Environmental and economic evaluation of the C&DW management scenarios: landfilling versus reuse/recycling.
Mann (2015)	To investigate the technical and legal compliance of C&DW management systems in Curitiba (Paraná State) from the application of a checklist in 24 building works.
Rosado (2015)	To develop a life cycle inventory of C&DW management system of Limeira (São Paulo State) in order to identify the best alternatives to minimize environmental impacts.
Cruvinel (2016)	To analyse the current C&DW management in Brasília and propose indicators of environmental sustainability.
Barreto (2016)	To analyse the current C&DW management of Palmas (Tocantins State), based on a theoretical framework of good practices and management, and carry out a C&DW classification and quantification during one year.
Caldas (2016)	To verify the performance of the C&DW management of João Pessoa (Paraíba State) in relation to the legislation.

Table A1.4. Dissertations about C&DW management system in Brazil (Part III).

Author (year)	Main objective
Palamin (2016)	To propose alternatives for the elaboration of the Municipal Management Plan of C&DW for small municipalities.
Alberici (2017)	To propose a sustainable management for C&DW from small generators in São Carlos (Santa Catarina State).
Lombardi Filho (2017)	To analyse the transport and destination of C&DW generated in São Paulo (São Paulo State) and propose a tutorial program to assist C&DW generating users.
Loch (2017)	To develop a model for assessing the legitimacy of the integrated municipal waste management plan.
Vargas (2018)	To analyse the state of art of the waste management in the construction sector in the State of Paraná and in the municipality of Cascavel.

APPENDIX A2 – LITERATURE REVIEW: LIFE CYCLE ASSESSMENT

This appendix reports additional information about the articles used in the Literature Review on LCA studies applied to C&DW management.

Table A2.1. Life cycle assessment studies about construnction and demolition waste management (Part I).

<table>
<tr><td colspan="2">Published in 2010</td></tr>
<tr><td colspan="2">Title: Environmental performance of construction waste: Comparing three scenarios from a case study in Catalonia, Spain</td></tr>
<tr><td colspan="2">Authors: O. Ortiz, J.C. Pasqualino and F. Castells</td></tr>
<tr><td colspan="2">Journal: Waste Management</td></tr>
<tr><td><i>Cited by</i> 125 (Google Scholar, 26th November 2018)</td><td><i>Journal Impact:</i> 4.723 (JCR, 2017)</td></tr>
<tr><td colspan="2">Title: Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix</td></tr>
<tr><td colspan="2">Authors: Gian Andrea Blengini and Elena Garbarino</td></tr>
<tr><td colspan="2">Journal: Journal of Cleaner Production</td></tr>
<tr><td><i>Cited by</i> 136 (Google Scholar, 26th November 2018)</td><td><i>Journal Impact:</i> 5.651 (JCR, 2017)</td></tr>
<tr><td colspan="2">Published in 2012</td></tr>
<tr><td colspan="2">Title: Influence of construction and demolition waste management on the environmental impact of buildings</td></tr>
<tr><td colspan="2">Authors: André Coelho and Jorge de Brito</td></tr>
<tr><td colspan="2">Journal: Waste Management</td></tr>
<tr><td><i>Cited by</i> 120 (Google Scholar, 26th November 2018)</td><td><i>Journal Impact:</i> 4.723 (JCR, 2017)</td></tr>
<tr><td colspan="2">Title: Life cycle assessment of construction and demolition waste management systems: a Spanish case study</td></tr>
<tr><td colspan="2">Authors: Irma T. Mercante, María D. Bovea, Valeria Ibáñez-Forés and Alejandro P. Arena</td></tr>
<tr><td colspan="2">Journal: The International Journal of Life Cycle Assessment</td></tr>
<tr><td><i>Cited by</i> 56 (Google Scholar, 26th November 2018)</td><td><i>Journal Impact:</i> 4.195 (JCR, 2017)</td></tr>
<tr><td colspan="2">Published in 2013</td></tr>
<tr><td colspan="2">Title: Life cycle assessment of end-of-life management options for construction and demolition debris</td></tr>
<tr><td colspan="2">Authors: Alberta Carpenter, Jenna R. Jambeck, Kevin Gardner, and Keith Weitz</td></tr>
<tr><td colspan="2">Journal: Journal of Industrial Ecology</td></tr>
<tr><td><i>Cited by</i> 22 (Google Scholar, 26th November 2018)</td><td><i>Journal Impact:</i> 4.356 (JCR, 2017)</td></tr>
<tr><td colspan="2">Title: End of life of buildings: three alternatives, two scenarios. A case study</td></tr>
<tr><td colspan="2">Authors: Eva Martínez, Yolanda Nuñez and Elena Sobaberas</td></tr>
<tr><td colspan="2">Journal: The International Journal of Life Cycle Assessment</td></tr>
<tr><td><i>Cited by</i> 18 (Google Scholar, 26th November 2018)</td><td><i>Journal Impact:</i> 4.195 (JCR, 2017)</td></tr>
<tr><td colspan="2">Title: An overview of construction and demolition waste management in Canada: a lifecycle analysis approach to sustainability</td></tr>
<tr><td colspan="2">Authors: Muluken Yeheyis, Kasun Hewage, M. Shahria Alam, Cigdem Eskicioglu, Rehan Sadiq</td></tr>
<tr><td colspan="2">Journal: Clean Technologies and Environmental Policy</td></tr>
<tr><td><i>Cited by</i> 152 (Google Scholar, 26th November 2018)</td><td><i>Journal Impact:</i> 2.337 (JCR, 2017)</td></tr>
</table>

Table A2.1. Life cycle assessment studies about construnction and demolition waste management (Part II).

Published in 2014

Title: Evaluating environmental impacts of alternative construction waste management approaches using supplychain-linked life-cycle analysis
Authors: Murat Kucukvar, Gokhan Egilmez and Omer Tatari
Journal: Waste Management & Research
Cited by 29 (Google Scholar, 26th November 2018) *Journal Impact:* 1.90 (JCR, 2015)

Published in 2015

Title: Life cycle assessment of construction and demolition waste management
Authors: Stefania Butera, Thomas H. Christensen and Thomas F. Astrup
Journal: Waste Management
Cited by 55 (Google Scholar, 26th November 2018) *Journal Impact:* 4.723 (JCR, 2017)

Published in 2016

Title: Comparison of scenarios for the integrated management of construction and demolition waste by life cycle assessment: A case study in Brazil
Authors: Carmenlucia Santos Giordano Penteado and Laís Peixoto Rosado
Journal: Waste Management & Research
Cited by 12 (Google Scholar, 26th November 2018) *Journal Impact:* 1.90 (JCR, 2015)

Title: Analysis of the environmental performance of life-cycle building waste management strategies in tertiary buildings
Authors: David Zambrana-Vasquez, Ignacio Zabalza-Bribían, Alberto Jáñez and Alfonso Aranda-Usón
Journal: Journal of Cleaner Production
Cited by 6 (Google Scholar, 26th November 2018) *Journal Impact:* 5.651 (JCR, 2017)

Published in 2017

Title: Comparative environmental evaluation of construction waste management through different waste sorting systems in Hong Kong
Authors: Md. Uzzal Hossain, Zezhou Wu and Chi Sun Poon
Journal: Waste Management
Cited by 19 (Google Scholar, 26th November 2018) *Journal Impact:* 4.723 (JCR, 2017)

Title: Consequential LCA modelling of building refurbishment in New Zealand - an evaluation of resource and waste management scenarios
Authors: Agneta Ghose, Massimo Pizzol and Sarah J. McLaren
Journal: Journal of Cleaner Production
Cited by 12 (Google Scholar, 26th November 2018) *Journal Impact:* 5.651 (JCR, 2017)

Title: Geospatial characterization of building material stocks for the lifecycle assessment of end-of-life scenarios at the urban scale
Authors: Alessio Mastrucci, Antonino Marvuglia, Emil Popovici, Ulrich Leopold and Enrico Benetto
Journal: Resources, Conservation and Recycling
Cited by 27 (Google Scholar, 26th November 2018) *Journal Impact:* 5.120 (JCR, 2017)

Title: Life cycle assessment of the end-of-life phase of a residential building
Authors: Pierluca Vitale, Noemi Arena, Fabrizio Di Gregorio and Umberto Arena
Journal: Waste Management
Cited by 26 (Google Scholar, 26th November 2018) *Journal Impact:* 4.723 (JCR, 2017)

Table A2.1. Life cycle assessment studies about construnction and demolition waste management (Part III).

Published in 2018

Title: Life cycle assessment of non-hazardous Construction and Demolition Waste (CDW) management in Lombardy Region (Italy)
Authors: Giulia Borghi, Sara Pantini and Lucia Rigamonti
Journal: Journal of Cleaner Production
Cited by 5 (Google Scholar, 26th November 2018) *Journal Impact:* 5.651 (JCR, 2017)

Title: Estimating the environmental costs and benefits of demolition waste using life cycle assessment and willingness-to-pay: A case study in Shenzhen
Authors: Ting Wang, Jiayuan Wang, Peng Wu, Jun Wang, Qinghua He and Xiangyu Wang
Journal: Journal of Cleaner Production
Cited by 18 (Google Scholar, 26th November 2018) *Journal Impact:* 5.651 (JCR, 2017)

Title: Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making
Authors: Andrea Di Maria, Johan Eyckmans and Karel Van Acker
Journal: Waste Management
Cited by 8 (Google Scholar, 26th November 2018) *Journal Impact:* 4.723 (JCR, 2017)

Title: Comparative LCA of wood waste management strategies generated from building construction activities
Authors: Md. Uzzal Hossain and Chi Sun Poon
Journal: Journal of Cleaner Production
Cited by 6 (Google Scholar, 26th November 2018) *Journal Impact:* 5.651 (JCR, 2017)

Title: Combining life cycle assessment and Building Information Modelling to account for carbon emission of building demolition waste: A case study
Authors: Jiayuan Wang, Huanyu Wu, Huabo Duan, George Zillante, Jian Zuo and Hongping Yuan
Journal: Journal of Cleaner Production
Cited by 8 (Google Scholar, 26th November 2018) *Journal Impact:* 5.651 (JCR, 2017)

Title: A bi-level environmental impact assessment framework for comparing construction and demolition waste management strategies
Authors: Ardavan Yazdanbakhsh
Journal: Waste Management
Cited by 0 (Google Scholar, 26th November 2018) *Journal Impact:* 4.723 (JCR, 2017)

Title: Inclusion of prevention scenarios in LCA of construction waste management
Authors: Nuria Bizcocho and Carmen Llatas
Journal: The International Journal of Life Cycle Assessment
Cited by 0 (Google Scholar, 06th December 2018) *Journal Impact:* 4.195 (JCR, 2017)

Title: Towards resource-efficient management of asphalt waste in Lombardy region (Italy): Identification of effective strategies based on the LCA methodology
Authors: Sara Pantini, Giulia Borghi and Lucia Rigamonti
Journal: Waste Management
Cited by 0 (Google Scholar, 06th December 2018) *Journal Impact:* 4.723 (JCR, 2017)

Table A2.2. General data about LCA studies on C&DW management, including the location, aim of the study and management strategies (Part I).

	Authors (year)	Location	Aim of the study	Management strategies
1	Ortiz, Pasqualino and Castells (2010)	Catalonia (Spain)	Evaluate the environmental impacts of C&DW in terms of the LIFE98 ENV/E/351 project, which aims at increase the environmental awareness in the construction sector.	Off-site recycling, incineration and landfilling.
2	Blengini and Garbarino (2010)	Provincia di Torino (Italy)	Analyse energy and environmental implications of the C&DW recycling chain in the administrative territory of Provincia di Torino in Northern Italy, take into account the transport distances, quality and availability of recycled aggregates and its geographic market coverage.	Off-site recycling.
3	Coelho and Brito (2012)	Portugal	Quantify the environmental impacts of building demolition, considering different scenarios of waste/material management, based on a “top-down” LCA methodology.	Off-site recycling and landfilling.
4	Mercante *et al*. (2012)	Spain	Present and analyse an inventory that includes the processes and materials involved in the C&DW management system in Spain, with emphasis on assessing the environmental profile of inert waste sorting and treatment facilities.	Off-site recycling and landfilling.
5	Carpenter *et al*. (2013)	New Hampshire (United States)	Develop an LCA of end-of-life management options for the C&DW generated in New Hampshire (United States), by using the U.S. Environmental Protection Agency’s Municipal Solid Waste Decision Support Tool.	Off-site recycling, combustion and landfilling.
6	Martínez, Nuñez and Sobaberas (2013)	Spain	Identify the most important processes for the environmental assessment of the end-of-life of a building, and the demolition process variables that significantly affect non-renewable energy consumption, human toxicity potential and greenhouse gases emissions.	Reuse, pre-treatment, off-site recycling, incineration and landfilling.
7	Yeheyis *et al*. (2013)	Canada	Propose a conceptual C&DW management framework to maximise the 3R (reduce, reuse and recycle) and minimise the C&DW landfilling, by implementing sustainable and comprehensive strategy throughout the lifecycle of construction projects.	Reuse, off-site recycling, composting, incineration and landfilling.
8	Kucukvar, Egilmez and Tatari (2014)	United States	Evaluate the environmental impacts (net carbon, energy and water footprints) by using an economic input–output-based hybrid LCA, taking into account nine different C&DW: concrete, wood, metals, paper, cardboard, plastic and glass.	Off-site recycling, incineration and landfilling.
9	Butera, Christensen and Astrup (2015)	Denmark	Evaluate the environmental impacts related to the end-of-life of mineral fraction of C&DW, considering its utilisation as unbound aggregate in road construction or landfill disposal, with special emphasis on leaching of inorganic contaminants.	Off-site recycling and landfilling.

Table A2.2. General data about LCA studies on C&DW management, including the location, aim of the study and management strategies (Part II).

Authors (year)		Location	Aim of the study	Management strategies
10	Penteado and Rosado (2016)	Limeira/São Paulo State (Brazil)	Comparison of the environmental impacts of the current C&DW management in a medium-sized municipality with six other proposed scenarios, considering the waste produced by small and large generators, in order to identify the best management alternatives.	Reuse, off-site recycling and landfilling.
11	Zambrama-Vasquez *et al*. (2016)	Zaragoza City (Spain)	Present a methodology, based on LCA, for evaluation of the environmental performance of different life-cycle building waste management strategies, considering the municipal solid waste generated during a building's use stage, and the C&DW generated during its construction and end-of-life.	Off-site recycling and landfilling.
12	Houssain, Wu and Poon (2017)	Hong Kong	Compare the environmental performance of building construction waste management systems in Hong Kong.	Reuse, off-site recycling and public fill/landfilling.
13	Ghose, Pizzol and McLaren (2017)	New Zealand	Verify if the material procurement and construction waste management strategies could reduce the environmental impacts at the same time as delivering the benefits of more energy efficient buildings.	Reuse, off-site recycling and landfilling.
14	Mastrucci *et al*. (2017)	Esch-sur-Alzette (Luxembourg)	Develop a framework for the characterisation of building material stocks and the assessment of the potential environmental impact associated with the end-of-life of buildings at the urban scale to support decision on waste management strategies.	Sorting plant (downcycling), off-site recycling, incineration and landfilling.
15	Vitale *et al*. (2017)	South of Italy	Investigate the potential environmental impacts related to the end-of-life phase of a residential building (multifamily dwelling of three levels), constructed in the South of Italy by utilizing conventional materials and up-to-date procedures.	Off-site recycling and landfilling.
16	Borghi, Pantini and Rigamonti (2018)	Lombardy Region (Italy)	Evaluate the environmental performance of the current C&DW management and to identify critical aspects and possible improving actions, with emphasis on the mixed non-hazardous waste (identified by the European Waste Code 170904).	Off-site recycling and landfilling.
17	Wang *et al*. (2018a)	Shenzhen City (China)	Investigate the environmental impacts of demolition waste recycling and landfilling in Shenzhen, by means of an LCA and willingness-to-pay methodologies.	Off-site recycling and landfilling.
18	Di Maria, Eyckmans and Acker (2018)	Flanders (Belgium)	Analyse the environmental and the economic drivers in four alternative C&DW end-of-life scenarios in the region of Flanders, in Belgium, by using a combined LCA and life cycle costing (LCC) methodologies.	Off-site recycling (downcycling, advanced and after selective demolition) and landfilling.

Table A2.2. General data about LCA studies on C&DW management, including the location, aim of the study and management strategies (Part III).

Authors (year)		Location	Aim of the study	Management strategies
19	Hossain and Poon (2018)	Hong Kong	Evaluate the environmental profile of the wood waste management, in order to minimize the environmental impacts and to provide a scientific basis for the decision-making process on the management systems.	Off-site recycling and landfilling.
20	Wang *et al*. (2018b)	Shenzhen City (China)	Propose a conceptual framework and calculation model to quantify the carbon emissions generated over the life cycle of building demolition waste by combined the Building Information Modelling (BIM) and LCA.	On-site recycling, off-site recycling and landfilling.
21	Yazdanbakhsh (2018)	New York City (United States)	Present a bi-level LCA framework for modelling alternative waste management approaches in which the impacts are measured and compared at two scales of strategy and decision-making, taking into account four potential management strategies for the mineral C&DW in New York City.	Off-site recycling and landfilling.
22	Bizcocho and Llatas (2018)	Seville (Spain)	Evaluate construction waste management scenarios that include waste prevention activities, by using a case study of new buildings in Spain as an illustration of the model approaches, which includes the comparison of four management scenarios.	Prevention, off-site recycling and landfilling.
23	Pantini, Borghi and Rigamonti (2018)	Lombardy Region (Italy)	Evaluate the current management of waste from deconstruction and milling of old pavements not containing tar (reclaimed asphalt pavement – RAP), in order to identify critical aspects and to suggest improvements.	Off-site recycling.

Table A2.3. Data on the LCA methodology of the C&DW management studies, including functional unit, C&DW composition, system boundaries and life cycle inventory data (Part I).

Author (year)		Functional unit	C&DW composition	Stages included in the system boundaries	Life cycle inventory data
1	Ortiz, Pasqualino and Castells (2010)	206 kg of waste/m^2 of constructed area (including new works, renovation and repairs).	Construction process and packaging material.	Collection; transport; inert, sanitary and hazardous landfilling; recycling (stones, metals, plastic, timber, paper/cardboard); incineration (plastic, paper/cardboard and special wastes).	*Primary data* from the LIFE98 ENV/E/351 project (transport distance from waste generation to landfill, recycling or incineration plant). *Secondary data* from Ecoinvent v2.01 (2007) database, adapted to the Spanish electrical mix and European transport system.
2	Blengini and Garbarino (2010)	1 t of collected and recycled C&DW.	Average composition from Provincia di Torino (Italy).	Collection; transport; recycling; recycled aggregates transport; avoided products (steel and natural aggregates) and avoided inert landfill.	*Primary data* from the database of Provincia di Torino or interviews with operators (amount of C&DW collection, recycling and landfilling, NA quarrying and land use); average distances were obtained from a GIS model. *Secondary data* from Ecoinvent 2.0 database (2006).
3	Coelho and Brito (2012)	1 m^2 of a reference building of Portugal.	Demolition of a reference building in Portugal.	Building demolition (complete and selective); transport; landfilling and recycling.	*Primary data* from real buildings and demolition operations (demolition operations, transport distances and management options). *Secondary data* from the literature, based on a “top-down approach” (environmental impacts of the materials and end-of-life of building).
4	Mercante *et al*. (2012)	1 t of C&DW.	Inert waste sorting and treatment plant (types I and II).	All the stages of the C&DW life cycle, from the on-site waste generation to its transformation into recycled material or its disposal on a landfill.	*Primary data* were collected directly from some Spanish enterprises involved in the life cycle of C&DW management. *Secondary data* from Ecoinvent (2008) database (materials, fuel and electricity).
5	Carpenter *et al*. (2013)	702,000 t of C&DW (total generated in New Hampshire in 2006).	Composition from New Hampshire.	Transport, processing, sorting, recycling, combustion to generate electricity and landfilling.	Primary data from the case study (specific wood composition, metal content, and energy content values). Secondary data from Municipal Solid Waste Decision Support Tool (default values for the non-wood materials).

Table A2.3. Data on the LCA methodology of the C&DW management studies, including functional unit, C&DW composition, system boundaries and life cycle inventory data (Part II).

Author (year)		Functional unit	C&DW composition	Stages included in the system boundaries	Life cycle inventory data
6	Martínez, Nuñez and Sobaberas (2013)	Demolition of a residential building (1,600 m² of built area).	Estimation of based on the waste generated in demolitions in Spain.	Demolition process; C&DW sorting and pre-treatment; transport; reuse; recycling; landfilling and incineration.	*Secondary data* from literature sources and Ecoinvent database (waste generated; energy consumption of hydraulic systems used in the demolition; emissions of particulate matter during the demolition process; distance of transport; waste treatment at the transfer plant - storage, milling and sieving/sorting; final disposal - landfill or incinerator municipal) updated with *primary data* from case study.
7	Yeheyis *et al*. (2013)[2]	Not applied.	Based on Canadian Construction Association (1992).	Not applied.	Not applied.
8	Kucukvar, Egilmez and Tatari (2014)	1 t of C&DW.	Based on Franklin Associates (1998) and the US EPA (2003).	Material production from virgin and recycled products; transport; material recovery; incineration with heat recovery and landfilling.	*Secondary data* from literature sources and databases/software, such as US EPA's WARM (2010), WASTED model (2006) and National Renewable Energy Laboratory (2010).
9	Butera, Christensen and Astrup (2015)	Management of 1 Mg of C&DW obtained after sorting at source (demolition or construction site).	Material includes concrete, possibly mixed with soil, tiles, bricks and mortar.	Transport; treatment processes; utilisation in road construction; landfilling (leaching of inorganic pollutants was included); substitution of virgin aggregates and related avoided emissions (avoided extraction from gravel pit, transport to the road construction site and leaching) and capital goods.	*Primary data* from the case study (C&DW composition, transport distances). *Secondary data* from literature sources and Ecoinvent database.

Table A2.3. Data on the LCA methodology of the C&DW management studies, including functional unit, C&DW composition, system boundaries and life cycle inventory data (Part III).

Author (year)		Functional unit	C&DW composition	Stages included in the system boundaries	Life cycle inventory data
10	Penteado and Rosado (2016)	Management of 0.8 t of C&DW classified as inert.	Inert fraction disposed in a municipal inert landfill, composed by soil, mixed C&DW, concrete and ceramics.	Transport; sorting; reuse; recycling; landfilling; avoided burdens (natural aggregates transport and extraction).	*Primary data* obtained from the sorting areas and landfill through the application of questionnaires (data on C&DW management). *Secondary data* from literature sources and Ecoinvent database (v.3.1), updated with the Brazilian energy mix.
11	Zambrama-Vasquez *et al*. (2016)	1 t of MSW and C&DW generated, collected and treated during the life cycle of a building.	Construction waste composition based on the literature; source of the demolition waste composition not informed.	Collection; transport; sorting; recycling and landfilling.	*Primary data* from the case study (inventory analysis of the construction and packaging waste generated during the construction and demolition). *Secondary data* from Ecoinvent v2.0 database, environmental product declarations and literature sources.
12	Houssain, Wu and Poon (2017)	1 t of construction waste.	Construction waste generated in two construction sites of residential buildings.	Transport; sorting, public fill or landfill disposal; recovery and reuse; transformation and valorisation into secondary products.	*Primary data* from two real building construction. *Secondary data* from literature sources and databases (China Light and Power, Chinese Life Cycle Database, European reference Life Cycle Database and Ecoinvent).
13	Ghose, Pizzol and McLaren (2017)	Demand for refurbishment and subsequent use of 1 m² gross floor area in an office building.	Based on the building prototypes modelled in the EnergyPlus and SketchUp software.	Raw material extraction and processing; product manufacture; product transport to the construction site and construction process; transport and waste management of demolished material produced during the refurbishment.	*Secondary data* from literature sources (foreground processes) and Ecoinvent v3 (2013) (background processes).

Table A2.3. Data on the LCA methodology of the C&DW management studies, including functional unit, C&DW composition, system boundaries and life cycle inventory data (Part IV).

Author (year)		**Functional unit**	**C&DW composition**	**Stages included in the system boundaries**	**Life cycle inventory data**
14	Mastrucci *et al*. (2017)	Overall net usable area of the building (1550 m²).	Based on National Waste Management Plan of Luxembourg.	Demolition operations; transport to the treatment plants and final waste treatments; credits for recycling and downcycling.	*Primary data* from the case study updated with *secondary data* from literature sources, national statistics, technical reports, guidelines and previous studies. Ecoinvent 2.2 (2010) database for the background inventory data.
15	Vitale *et al*. (2017)	Overall net usable area of the building (1550 m²).	C&DW generated by the demolition of the reference building.	All the activities of selective demolition; collection; sorting; transport; material and energy recovery and landfilling.	Most of the environmental burdens (direct, indirect, and avoided) have been obtained processing data deriving from scientific papers as well as technical visits and interviews to operators of small and medium enterprises active in areas of South of Italy. The remaining, mainly indirect, burdens derived from the database Ecoinvent 3.01.
16	Borghi, Pantini and Rigamonti (2018)	1 t of non-hazardous C&DW mixture managed in 2014.	Based on the case study (cement, tiles and ceramics and mixed waste).	Unloading, moving and uploading CDW in transfer stations; recycling processes; treatment of the fractions separated from the inert mineral fraction (i.e. recycling of ferrous metals and landfilling of unrecoverable residues); C&DW disposal; natural aggregates avoided production; primary steel avoided production; transport of C&DW to plants, transport of RAs from recycling plants to final users and transport of NAs from quarries to final users.	*Primary data* from the case study (recycling processes, avoided production of NAs, C&DW transport to the treatment plants and, waste storage operations). *Secondary data* from literature and Ecoinvent 3.3 database (CDW disposal and ferrous metals recycling), with modifications in some datasets.

Table A2.3. Data on the LCA methodology of the C&DW management studies, including functional unit, C&DW composition, system boundaries and life cycle inventory data (Part V).

Author (year)		Functional unit	C&DW composition	Stages included in the system boundaries	Life cycle inventory data
17	Wang *et al*. (2018a)	1 t of demolition waste from demolished buildings.	Composition of demolition waste in Shenzhen (concrete, brick, mortar and metal).	On-site sorting and pre-treatment; transport from a demolition site to a waste treatment plant; recycling processes; landfilling and recycling credits.	*Primary data* from the case study (transport distance from a demolition site to a waste treatment plant and demolition waste composition). *Secondary data* from the literature sources (brick recycling, production of steel, diesel and electricity) and Ecoinvent database (2016).
18	Di Maria, Eyckmans and Acker (2018)	Treatment of 840,000 t of C&DW/year.	Average C&DW composition in Belgium based on Deloitte report (2015).	Building demolition; transport; landfilling; traditional and advanced recycling; credits of recycling.	*Primary data* from the case study (transport distances). *Secondary data* from the literature and Ecoinvent database.
19	Hossain and Poon (2018)	1 t of wood waste.	Not applied.	On-site sorting and collection; transport stages; store in open and dry place; recycling processes; baggage and store; energy generation from wood pellets; landfilling and credits of recycling.	*Primary data* obtained from recycling factory (foreground processes) and *secondary data* from literature, previous studies, environmental product declaration and databases (Chinese Life Cycle Database and Ecoinvent).
20	Wang *et al*. (2018b)	14,803.12 t of demolition wastes.	Based on data from Building Information Model of specific cases.	Demolition stage; collection and sorting; transport; recycling processes; landfilling and credits of recycling.	*Primary data* of demolition process were obtained from a series of interviews to the project managers in companies related to the case study. The remaining data *(secondary data)* were obtained from literature review and Ecoinvent 3 database.

Table A2.3. Data on the LCA methodology of the C&DW management studies, including functional unit, C&DW composition, system boundaries and life cycle inventory data (Part VI).

Authors (year)		Functional unit	C&DW composition[1]	Stages included in the system boundaries	Life cycle inventory data
21	Yazdanbakhsh (2018)	Managing all the available mineral C&DW.	Based on City of New York Department of Sanitation.	Transport; recycling; landfilling and credits of recycling.	*Primary data* from City of New York Department of Sanitation, collected from 21 waste management facilities. *Secondary data* from literature and Ecoinvent v. 3.3 database (with modifications in the datasets).
22	Bizcocho and Llatas (2018)	Management of the waste generated during the construction of a 13,910 m² residential building in Seville.	Composition based on the project of the selected building.	Downstream processes (transport, waste processing and disposal) and upstream processes (raw material supply, transport and manufacturing).	*Secondary data* from literature sources and Ecoinvent v2 database.
23	Pantini, Borghi and Rigamonti (2018)	1 t of non-hazardous asphalt waste.	75% hot-mix asphalt and 25% cold-mix asphalt.	Transport from road worksites to the recycling plants; pre-processing; recycling; avoided production of natural aggregates; avoided production and transport of virgin bitumen; manufacturing and transport of rejuvenating agents, bitumen emulsion and concrete.	*Primary data* collected from several sources (MUD declarations, Provinces' documents, asphalt manufacturing plants, some road companies). *Secondary data* related to other foreground processes were taken from Ecoinvent 3.3 database (allocation, recycled content).

Table A2.4. Data on the LCA methodology of the C&DW management studies, including life cycle impact assessment methodology, aspects considered in the sensitivity analysis and software utilised (Part I).

Author (year)		**LCIA methodology**	**LCIA optional steps**	**Aspects considered in the sensitivity analysis**	**Software**
1	Ortiz, Pasqualino and Castells (2010)	CML 2 baseline 2000.	Not applied.	Management scenario (incineration with recycling). Variations in the transport distances.	LCAManager developed by SIMPPLE SL.
2	Blengini and Garbarino (2010)	IMPACT 2002+ and Eco-Indicator 99.	Normalisation (per capita yearly impacts of one European citizen) and normalisation of the endpoint indicators.	Variations in the transport distances.	SimaPro 7.
3	Coelho and Brito (2012)	Only the impact categories were mentioned.	Not applied.	Not applied.	Not applied.
4	Mercante *et al*. (2012)	CML (2002).	Not applied.	Not applied.	SimaPro 7.3.
5	Carpenter *et al*. (2013)	Only the impact categories were mentioned.	Normalisation (the impact annually generated per capita in the United States).	Assessment of the basis chosen for determining the energy offset affect the energy offset results and energy contents of C&D wood debris.	U.S. Environmental Protection Agency's Municipal Solid Waste Decision Support Tool.
6	Martínez, Nuñez and Sobaberas (2013)	CML (2001) baseline and cumulative energy demand.	Not applied.	Scenario analysis with the comparison of selective and conventional demolition processes.	SimaPro 7.2.4.
7	Yeheyis *et al*. (2013)	Not applied.	Not applied.	Not applied.	Not applied.
8	Kucukvar, Egilmez and Tatari (2014)	Only the impact categories were mentioned.	Not applied.	Not applied.	US EPA's WARM and WASTED model.

Table A2.4. Data on the LCA methodology of the C&DW management studies, including life cycle impact assessment methodology, aspects considered in the sensitivity analysis and software utilised (Part II).

Author (year)		LCIA methodology	LCIA optional steps	Aspects considered in the sensitivity analysis	Software
9	Butera, Christensen and Astrup (2015)	ILCD-recommended midpoint categories (2013).	Normalisation (per capita yearly impacts of one European citizen).	Sensitivity analysis for transport (comparison scenarios with EURO 3 versus EURO 5 transport trucks).	EASETECH.
10	Penteado and Rosado (2016)	CML 2 baseline 2001 methodology.	Normalisation (per capita yearly impacts of one person in World).	Not applied.	Not applied.
11	Zambrama-Vasquez *et al*. (2016)	IPCC 2007 GWP 100a v1.02.	Not applied.	Scenario analysis: construction waste recovery and demolition waste recovery.	SimaPro 7.3.2.
12	Houssain, Wu and Poon (2017)	IMPACT 2002+.	Weighting.	Influence of materials recovery rates on the environmental profile.	SimaPro 8.1.0
13	Ghose, Pizzol and McLaren (2017)	CML; ILCD 2011+ and ReCiPe (H) methodologies.	Not applied.	Sensitivity analysis of the recycling efficiency, specific marginal suppliers, and potential change in electricity grid mix.	Not applied.
14	Mastrucci *et al*. (2017)	CML 2 baseline 2000.	Normalisation (factors for the year 1995 covering Western Europe).	Not applied.	SimaPro 7.3.3.
15	Vitale *et al*. (2017)	Impact 2002+ v2.11.	Normalisation (per capita yearly impacts of one European citizen).	Different criteria for the demolition process, management of demolition waste and assessment of avoided burdens of the main recycled materials.	SimaPro 8.0.2.
16	Borghi, Pantini and Rigamonti (2018)	ILCD 2011, cumulative energy demand, kg of sand and gravel consumed or saved.	Not applied.	Scenario analysis on the method for the management system; recycling facilities; transport distances; replacement coefficient, and quality of recycled aggregates.	SimaPro 8.3.

Table A2.4. Data on the LCA methodology of the C&DW management studies, including life cycle impact assessment methodology, aspects considered in the sensitivity analysis and software utilised (Part III).

Author (year)		LCIA methodology	LCIA optional steps	Aspects considered in the sensitivity analysis	Software
17	Wang *et al.* (2018a)	Only the impact categories were mentioned.	Not applied.	Not applied.	Not applied.
18	Di Maria, Eyckmans and Acker (2018)	ReCiPe 1.08 (H/H).	Weighting (per capita yearly impacts of one European citizen).	Perturbation analysis (variation of 15 parameters).	Gabi.
19	Hossain and Poon (2018)	IMPACT 2002 +.	Not applied.	Sensitivity analysis for the varying wood waste transport distance.	SimaPro 8.1.0.
20	Wang *et al.* (2018b)	IPCC 2013 GWP 100a v1.01.	Not applied.	Not applied.	SimaPro 8.1.
21	Yazdanbakhsh (2018)	TRACI 2.1.	Not applied.	Not applied.	Not applied.
22	Bizcocho and Llatas (2018)	CML 2001.	Not applied.	Not applied.	SimaPro 7.1.
23	Pantini, Borghi and Rigamonti (2018)	ILCD 2011 and Cumulative Energy Demand.	Not applied.	Sensitivity analysis on the transport of the asphalt waste, virgin bitumen, cement and chemical additives.	SimaPro 8.3.

Table A2.5. Impact categories selected by the LCA studies on C&DW management (Part I).

	Authors (year)	Midpoint impact categories													Endpoint impact categories				Other indicators			
		AC	**GW**	**EC**			**EU**	**HT**	**IR**	**LU**	**OD**	**POF**	**RD**	**RI**	**HH**	**EQ**	**CC**	**R**	**RE**	**NRE**	**ME**	**WU**
				f	**m**	**t**																
1	Ortiz, Pasqualino and Castells (2010)	x	x	x		x	x	x											x	x	x	x
2	Blengini and Garbarino (2010)	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x				
3	Coelho and Brito (2012)[1]	x	x				x					x										
4	Mercante *et al*. (2012)	x	x				x				x	x										
5	Carpenter *et al*. (2013)[2]		x																x	x		
6	Martínez, Nuñez and Sobaberas (2013)		x					x												x		
7	Yeheyis *et al*. (2013)	*Theorical LCA study.*																				
8	Kucukvar, Egilmez and Tatari (2014)		x																	x		x
9	Butera, Christensen and Astrup (2015)	x	x	x			x	x	x		x	x	x	x								
10	Penteado and Rosado (2016)	x	x				x					x	x									
11	Zambrama-Vasquez *et al*. (2016)		x																			
12	Houssain, Wu and Poon (2017)	x	x				x				x			x						x		
13	Ghose, Pizzol and McLaren (2017)	x	x	x			x	x	x		x	x	x	x							x	

Legend: AC – Acidification; GW – Global warming; EC – Ecotoxicity (f – freshwater; m – marine; t – terrestrial); EU – Eutrophication; HT – Human toxicity; IR – Ionising radiation; LU – land use; OD - Ozone layer depletion; POF - Photochemical ozone formation; RD – Resource depletion; RI – Respiratory inorganic; HH – human health; EQ – Ecosystem quality; CC – Climate change; R – Resources; RE – Renewable energy; NRE – Non-renewable energy; ME – mineral extraction; WU – Water use. [1]This study also evaluate the heavy metals (kg Pb eq/m² of building). [2]This study also evaluates the air emissions of lead, and the emission to water of lead, arsenic, zinc, cadmium, chromium, copper, mercury, and selenium.

Table A2.5. Impact categories selected by the LCA studies on C&DW management (Part II).

Authors (year)		**Midpoint impact categories**													**Endpoint impact categories**				**Other indicators**			
		AC	**GW**	**EC**			**EU**	**HT**	**IR**	**LU**	**OD**	**POF**	**RD**	**RI**	**HH**	**EQ**	**CC**	**R**	**RE**	**NRE**	**ME**	**WU**
				f	**m**	**t**																
14	Mastrucci *et al.* (2017)	x	x				x				x	x	x									
15	Vitale *et al.* (2017)		x			x		x		x				x						x	x	
16	Borghi, Pantini and Rigamonti (2018)[1]	x	x	x			x	x			x	x	x	x								x
17	Wang *et al.* (2018a)[2]	x	x				x			x	x											
18	Di Maria, Eyckmans and Acker (2018)[3]	*All impact categories of ReCiPe 1.08 (H/H) weighting methodology.*																				
19	Hossain and Poon (2018)		x																	x		
20	Wang *et al.* (2018b)		x																			
21	Yazdanbakhsh (2018)[3]	x	x				x	x			x	x		x								
22	Bizcocho and Llatas (2018)[4]	x	x				x	x			x	x										
23	Pantini, Borghi and Rigamonti (2018)[1]	x	x	x			x	x			x	x	x	x								x

Legend: AC – Acidification; GW – Global warming; EC – Ecotoxicity (f – freshwater; m – marine; t – terrestrial); EU – Eutrophication; HT – Human toxicity; IR – Ionising radiation; LU – land use; OD - Ozone layer depletion; POF - Photochemical ozone formation; RD – Resource depletion; RI – Respiratory inorganic; HH – human health; EQ – Ecosystem quality; CC – Climate change; R – Resources; RE – Renewable energy; NRE – Non-renewable energy; ME – mineral extraction; WU – Water use. [1]This study also included the Cumulative Energy Demand and non-renewable virgin raw material consumption, expressed in terms of kg of sand and gravel consumed or saved. [2]This study also considered suspended particulate matter and solid waste as impact categories. [3]This study also include ecotoxicity and fossil fuel depletion.[4]This study also included the Cumulative Energy Demand.

Table A2.6 Main results, conclusions and contribution of the LCA studies on C&DW management (Part I).

	Author (year)	**Main results and conclusions**	**Main contributions**
1	Ortiz, Pasqualino and Castells (2010)	Construction waste recycling is the recommended option, followed by landfilling and incineration. This study highlights the influence of transport for the environmental impacts.	It was one of the first studies focused on the evaluation of the environmental impacts of construction waste.
2	Blengini and Garbarino (2010)	The LCA of the C&DW recycling chain in Turin showed that avoided impacts are higher than induced impacts. It was also estimated that the transport distance of recycled aggregate should increase 2–3 times before the induced impacts outweigh the avoided impacts.	The application of GIS model combined with LCA provided a reliable simulation of transport stages. This study highlighted that when modelling land use of mining/recycling activities, site specific data are highly recommended, as Ecoinvent database may be inconsistent.
3	Coelho and Brito (2012)	The results showed that selective demolition may not reduce the environmental impacts, mainly due to the need of extra transport. However, the sorting of the main material into demolition operations and their recycling and/or reuse provided environmental benefits.	To develop a “top down” LCA rather than ‘bottom-up’, which usually involves large amounts of data and required the use of specific software.
4	Mercante *et al*. (2012)	Environmental impacts of inert waste sorting and treatment can be reduced by selective collection at source, since it avoids the separation of light fractions in the facilities. Transport stage plays a decisive role.	The containers (skip bins) contribute to less than 1% for the total impacts of all categories.
5	Carpenter *et al*. (2013)	In general, C&DW recycling is more favourable than C&DW landfilling, even without wood combustion to generate electricity.	A set of data about the characteristics and management of wood from C&DW.
6	Martínez, Nuñez and Sobaberas (2013)	The main environmental burdens related to selective demolition are: waste transport from the demolition work to the treatment plant or to the final disposal and, the fuel consumption by the equipments used in the demolition and treatment facilities. The main environmental burdens related to a conventional demolition is waste transport from the demolition work to final disposal.	Highlighted the importance of further study to assess the particulate matter emissions during the demolition processes (selective and conventional).
7	Yeheyis *et al*. (2013)	Propose a conceptual integrated C&DW management framework divided into three life cycle stages of the construction project: the pre-construction (planning and design), the construction and renovation stages and the demolition, based on the 3R approach.	The proposal is important to conducted LCA studies on C&DW management, since it provides an overview of a sustainable C&DW management.
8	Kucukvar, Egilmez and Tatari (2014)	Recycling of concrete, drywall, and wood did not have a significant contribution to the net environmental footprint savings. The results indicated that recycling of ferrous and non-ferrous metals improve the environmental sustainability. Landfilling and incineration can be considered as a secondary strategy after recycling.	Provided results of the environmental impacts related to nine different types of C&DW and six major building sectors.

Table A2.6. Main results, conclusions and contribution of the LCA studies on C&DW management (Part II).

Author (year)		Main results and conclusions	Main contributions
9	Butera, Christensen and Astrup (2015)	C&DW utilisation in road construction was preferable to landfilling for most impact categories. Transport represented the most important contribution for most non-toxic impacts. Leaching played a critical role for the toxicity categories, where landfilling had lower impacts than utilisation. Capital goods contributed with negligible impacts.	Compared with the overall life cycle of building and construction materials, leaching emissions were shown to be potentially significant for toxicity impacts.
10	Penteado and Rosado (2016)	The results highlighted that recycling is beneficial when efficient C&DW sorting takes place at construction sites, avoiding the transport of refuse to sorting and recycling facilities.	The development of a LCA on a municipal C&DW management system.
11	Zambrama-Vasquez *et al*. (2016)	The increase of the recovery rates of metals wastes provided greater benefits in terms of the global warming. The recovery of demolition materials, in replacement of virgin building materials, saves capacity of landfills.	The detailed analysis of the building design phase presented in this study enables to predict the C&DW generation and their environmental implications for management purposes.
12	Houssain, Wu and Poon (2017)	The C&W management system by using off-site sorting and direct landfilling resulted in significant environmental impacts. However, a considerable net environmental benefit was observed through an on-site sorting system.	The assessment of different waste sorting strategies on the environmental performance of building C&W management systems would be valuable to assess the economic feasibility.
13	Ghose, Pizzol and McLaren (2017)	Increasing the rates of construction waste recovery and reuse at site can reduce the overall environmental impact of a building refurbishment compared to use of construction materials with recycled content. The net impact results were sensitive to the quality of recyclable material, location of the marginal supplier and marginal energy source.	The outcome of this study can assist both policy makers and stakeholders in the building sector, and LCA practitioners.
14	Mastrucci *et al*. (2017)	The recycling from 50% to 70% of inert materials resulted in an average reduction of 25.6% on abiotic depletion potential and 9.2% on global warming.	The methodology combined a bottom-up material stock model based on geographical information systems and a spatial–temporal database with LCA.
15	Vitale *et al*. (2017)	The selective demolition could increase the quality and quantity of wastes recovered and safely disposed. The recycling of reinforcing steel presented an important role, accounting for 65% of the total avoided impacts related to respiratory inorganics, 89% of those for global warming and 73% of those for mineral extraction.	The results can be use by the European Union to propose recommendations on selective demolition in the action plan for the Circular Economy.

Table A2.6. Main results, conclusions and contribution of the LCA studies on C&DW management (Part III).

Author (year)		Main results and conclusions	Main contributions
16	Borghi, Pantini and Rigamonti (2018)	The LCA of the current C&DW management system showed that the induced environmental impacts are higher than the benefits from recycling. However, the current system performs better than a scenario where all the C&DW is landfilled.	Development of a methodology to determine the substitution factor for recycled aggregates. Recommendations were formulated to improve the environmental performance of the current management system.
17	Wang *et al*. (2018a)	The results showed that recycling can bring an environmental benefit of ¥1.21 per tonne, while direct landfilling leads to an environmental cost of ¥12.04 per tonne.	The results can be used by regulatory authorities to establish strategies and policies, such as the provision of monetary incentives to encourage recycling activities. The results can also be used to establish appropriate landfill tax.
18	Di Maria, Eyckmans and Acker (2018)	Implementing a high landfill tax, increasing the gate fee to the recycling plant, and boosting the sales price of recycled aggregates are the most effective drivers to facilitate a transition towards a more sustainable C&DW management system.	This study demonstrated that the combined LCA and LCC results are an useful tool to to support sustainable policy making.
19	Hossain and Poon (2018)	The energy generation from bio-fuel derived from wood waste was the best strategy. In addition, significant reductions of environmental impacts were observed for the production of particleboard and wood-cement composite from wood waste compared to the use of virgin wood.	This study provided guidelines to design a sustainable and resource-efficient wood waste management system.
20	Wang *et al*. (2018b)	The environmental benefit derived from recycling of building demolition waste varies from one material to another (e.g. recycling of metal has higher environmental benefits compared to masonry wastes).	Development of large-scale inventories, which provide useful inputs to improve the recycling of building demolition waste, reducing associated carbon emissions.
21	Yazdanbakhsh (2018)	The bi-level LCA framework developed was able to determine if the use of recycled aggregates in substitution of natural aggregates is environmentally competitive compared to other waste management alternatives.	The model can be used to perform sensitivity analyses and dynamic LCA. In addition, it is particularly useful for project-specific studies where accurate local data are available.
22	Bizcocho and Llatas (2018)	Prevention was the most favourable scenario, reducing by 60% the amount of construction waste generated and, at least 60% of all impacts of the categories analysed.	Development of a methodology that allow a greater insight into the effects on the environment of prevented construction waste, which could support further LCA studies.
23	Pantini, Borghi and Rigamonti (2018)	Results indicate that recycling reclaimed asphalt pavement (RAP) in hot/cold mixes is significantly more beneficial than its recovery as unbound material.	Provided some recommendations to the local government to further improve the management of asphalt waste and highlighted the absence of primary data related to the production of bitumen emulsion and cement.

APPENDIX A3 – QUESTIONNARIE

This appendix reports the questionnaire used for primary data gathering of the representative municipalities. The questionnaire was approved by the Ethics Committee of University of Campinas (CEP - UNICAMP), with the Certificate of Presentation for Ethical Appreciation (CAAE) number 52961316.3.0000.5404. The interviewees agreed to the survey by signing the "Authorization for Data Collection" and the "Free Informed Consent Term", these documents are archived in the CEP online system.

School of Technology – University of Campinas

Postgraduate Program in Technology for the Environment

Research project: “Life Cycle Assessment of Construction and Demolition Waste Management in a large area of São Paulo State, Brazil.

Researcher: Laís Peixoto Rosado

Advisor: Professor Dr. Carmenlucia Santos G. Penteado

QUESTIONNARIE

Municipality/Consortium:

Name:

Office:

Department:

1. Does the municipality have the Municipal C&DW Management Plan? Is it available on the internet?

2. What are the main municipal laws applied to the C&DW management? How does the municipality classify small and large C&DW generators?

3. What is the annual and per capita generation of C&DW?

4. What are the structures for the C&DW management (sorting areas, landfills and recycling facilities)? How do they work?

5. How does work the management of C&DW from small generators?

6. How does work the management of C&DW from large generators? Are the C&DW Management Plans of large construction works required and controlled?

7. How does work the management of C&DW generated in public construction sites?

8. Are the C&DW transport companies registered and monitored? If yes, how does this work?

9. Are the sites of C&DW illegal disposal registered? Are there the application of warnings or fines for the responsible that perform the illegal disposal?

10. How many employees are involved in the C&DW management system?

11. Is there an environmental education program for C&DW?

12. Are there any future projects for improvements in the municipal C&DW management system?

13. What are the main difficulties and challenges in relation to the C&DW management?

***General comments and notes:**

AUTHORIZATION FOR DATA COLLECTION

Autorização para Coleta de Dados

Eu, **nome**, **profissão** da **Prefeitura de município**, declaro estar ciente dos requisitos da Resolução CNS/MS 466/12 e suas complementares e declaro que tenho conhecimento dos procedimentos/instrumentos aos quais os participantes da presente pesquisa serão submetidos. Assim autorizo a coleta de dados do projeto de pesquisa intitulado **"Avaliação do Ciclo de Vida de Alternativas para o Gerenciamento dos Resíduos da Construção Civil nos Municípios das Bacias Hidrográficas dos Rios Piracicaba, Jundiaí e Capivari (UGRHI-05)"**, sob-responsabilidade da pesquisadora **Laís Peixoto Rosado** após a aprovação do referido projeto de pesquisa pelo Comitê de Ética em Pesquisa-Unicamp.

____

Assinatura e carimbo
Data:

FREE INFORMED CONSENT TERM

TERMO DE CONSENTIMENTO LIVRE E ESCLARECIDO

Avaliação do Ciclo de Vida de Alternativas para o Gerenciamento dos Resíduos da Construção Civil nos Municípios das Bacias Hidrográficas dos Rios Piracicaba, Capivari e Jundiaí (UGRHI-05).

Nome dos responsáveis: Laís Peixoto Rosado e Carmenlucia Santos Giordano Penteado.
Número do CAAE: 52961316.3.0000.5404.

Você está sendo convidado a participar como voluntário de um estudo. Este documento, chamado Termo de Consentimento Livre e Esclarecido, visa assegurar seus direitos e deveres como participante e é elaborado em duas vias, uma que deverá ficar com você e outra com o pesquisador.

Por favor, leia com atenção e calma, aproveitando para esclarecer suas dúvidas. Se houverem perguntas antes ou mesmo depois de assiná-lo, você poderá esclarecê-las com o pesquisador. Se preferir, pode levar para casa e consultar seus familiares ou outras pessoas antes de decidir participar. Se você não quiser participar ou retirar sua autorização, a qualquer momento, não haverá nenhum tipo de penalização ou prejuízo.

Justificativa e objetivos:

O crescimento exponencial da população e da urbanização, juntamente com as atividades de construção, demolição e reforma, resultou no aumento da geração dos resíduos da construção civil (RCC) em todo o mundo. Nesse sentido, o sistema de gerenciamento dos resíduos da construção civil (SGRCC) é um componente chave para evitar ou minimizar os efeitos adversos das atividades econômicas, com vistas a proteção do meio ambiente. Para realizar um estudo dos impactos dos SGRCC, a Avaliação do Ciclo de Vida (ACV) é uma das ferramentas mais indicadas para avaliar os impactos de cada etapa do gerenciamento.

Diante do exposto, este trabalho pretende avaliar o desempenho do sistema de gerenciamento de resíduos da construção civil que integram a 5ª Unidade de Gerenciamento de Recursos Hídricos (UGRHI-5) do Estado de São Paulo. A avaliação será realizada de acordo com a metodologia de ACV, com a finalidade de subsidiar as ações do poder público municipal, provendo informações sobre os impactos ambientais atuais bem como a proposição de melhorias, por meio de simulações de cenários incluindo outras formas de tratamento e destinação final.

Procedimentos:

Participando do estudo você está sendo convidado a: responder um questionário sobre o sistema municipal de gerenciamento dos resíduos sólidos, com ênfase para os resíduos da construção civil e resíduos volumosos. As informações solicitadas no questionário referem-se à quantidade gerada, manejo dos resíduos, infraestruturas existentes e projetos futuros. O tempo médio para responder as questões é de uma hora, sendo que não haverá gravação de áudio durante a entrevista.

Desconfortos e riscos:

Não há desconforto ou riscos envolvidos nesta pesquisa. Você **não** deve participar deste estudo se não possui autorização para responder as questões sobre o sistema municipal de gerenciamento dos resíduos sólidos.

Benefícios:

Não há benefícios diretos ao participante da pesquisa.

Acompanhamento e assistência:

A tese de doutorado estará disponível para consultas da pesquisa e utilização dos resultados, caso seja viável.

Sigilo e privacidade:

Você tem a garantia de que sua identidade será mantida em sigilo e nenhuma informação será dada a outras pessoas que não façam parte da equipe de pesquisadores. Na divulgação dos resultados desse estudo, seu nome não será citado.

Ressarcimento:

Não haverá ressarcimento, reembolso ou premiação financeira ao participante da pesquisa. Não haverá nenhuma despesa, o pesquisador irá até o local para coletar as respostas do questionário, no horário agendado.

Contato:

Em caso de dúvidas sobre o estudo, você poderá entrar em contato com Profa. Dra. Carmenlucia Santos Giordado Penteado, Departamento – Coordenação dos Cursos de Engenharia Ambiental e Tecnologia em Saneamento Ambiental e Controle Ambiental da Faculdade de Tecnologia da UNICAMP - Rua Paschoal Marmo, 1888 - CEP: 13484-332 - Jd. Nova Itália - Limeira, SP, contato telefônico (19) 2113-3479 e e-mail: carmenlucia@ft.unicamp.br.

Em caso de denúncias ou reclamações sobre sua participação no estudo, você pode entrar em contato com a secretaria do Comitê de Ética em Pesquisa (CEP): Rua: Tessália Vieira de Camargo, 126; CEP 13083-887 Campinas – SP; telefone (19) 3521-8936; fax (19) 3521-7187; e-mail: cep@fcm.unicamp.br

Consentimento livre e esclarecido:

Após ter sido esclarecimento sobre a natureza da pesquisa, seus objetivos, métodos, benefícios previstos, potenciais riscos e o incômodo que esta possa acarretar, aceito participar:

Nome do(a) participante: ____

____ Data: ____/_____/______.

(Assinatura do participante ou nome e assinatura do responsável)

Responsabilidade do Pesquisador:

Asseguro ter cumprido as exigências da resolução 466/2012 CNS/MS e complementares na elaboração do protocolo e na obtenção deste Termo de Consentimento Livre e Esclarecido. Asseguro, também, ter explicado e fornecido uma cópia deste documento ao participante. Informo que o estudo foi aprovado pelo CEP perante o qual o projeto foi apresentado e pela CONEP, quando pertinente. Comprometo-me a utilizar o material e os dados obtidos nesta pesquisa exclusivamente para as finalidades previstas neste documento ou conforme o consentimento dado pelo participante.

____ Data: ____/_____/______.

(Assinatura do pesquisador)

APPENDIX A4 – LIFE CYCLE IMPACT ASSESSMENT DATA: CML BASELINE V3.03 METHODOLOGY

This appendix reports supplementary data of life cycle impact assesment obtained by using the CML baseline v3.03 methodology.

Figure A4.1. Normalised results of impact assessment related to the C&DW management system in the base case scenario, obtained from normalised factors for World (2000) and for Europe (2000) of CML baseline methodology.

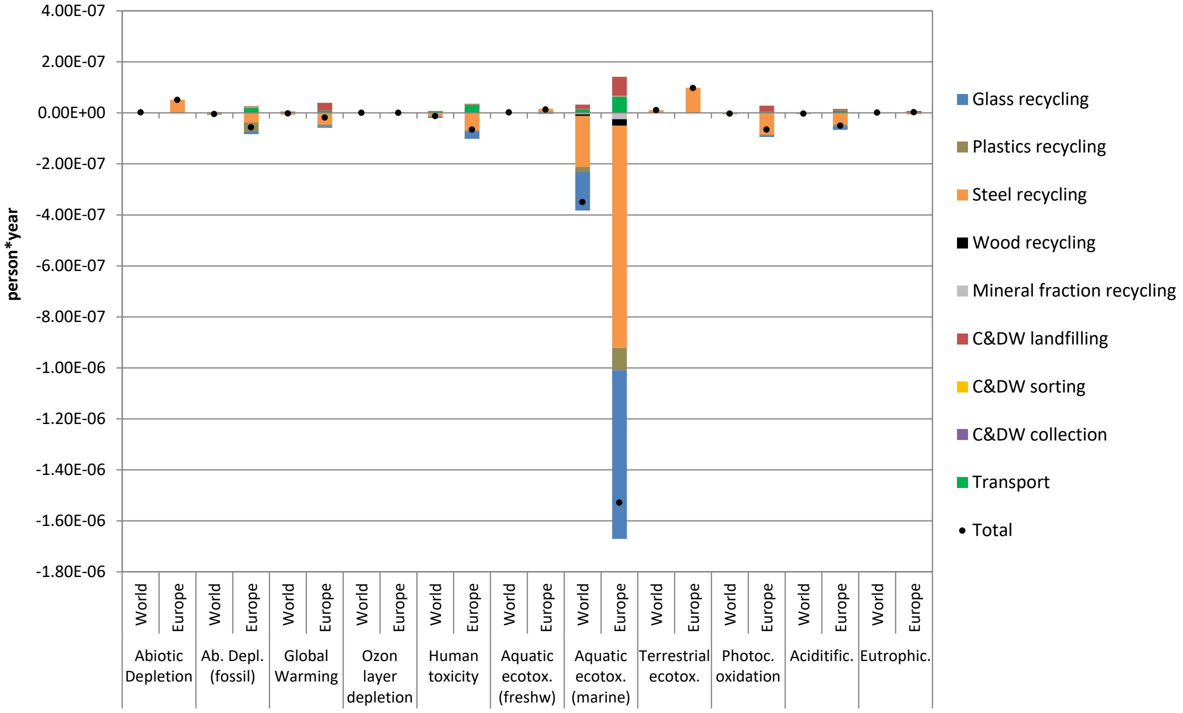
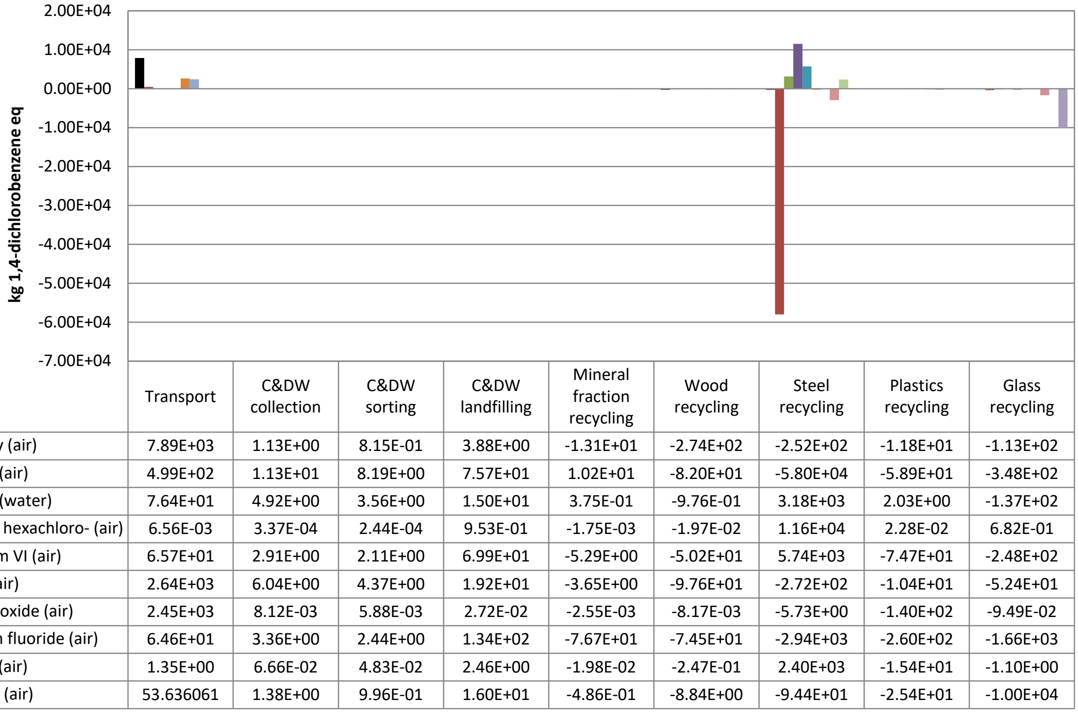
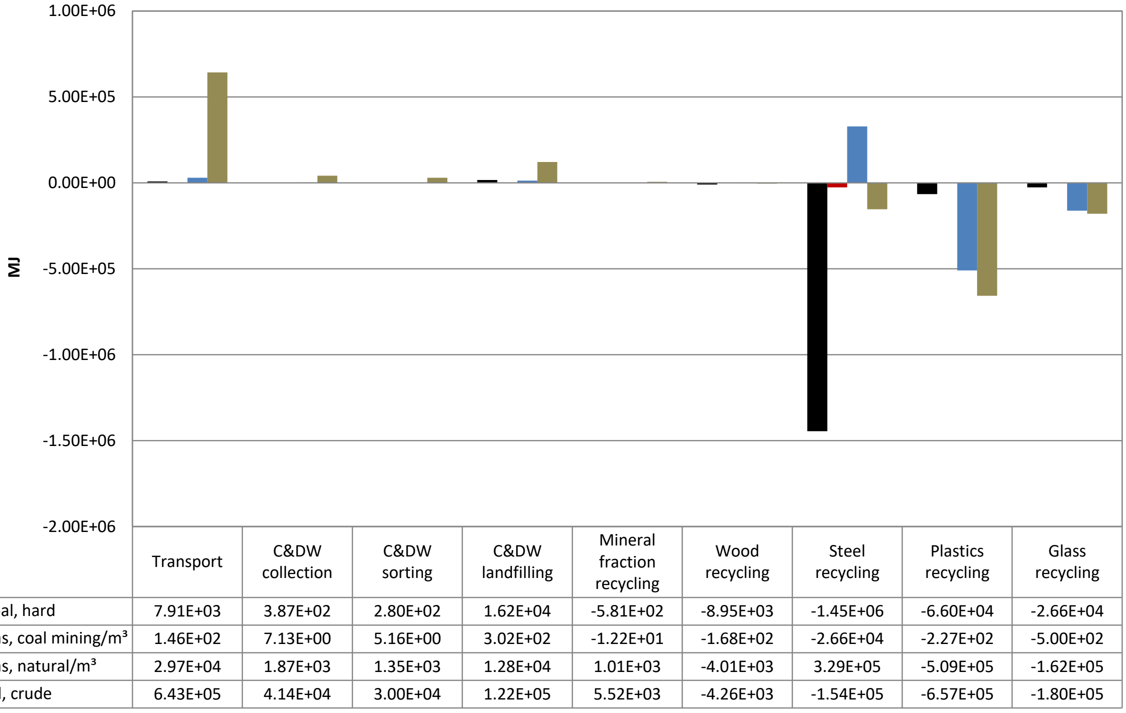


Figure A4.2. Contribution analysis for the impact category “Human Toxicity” for the C&DW management system in the base case scenario.



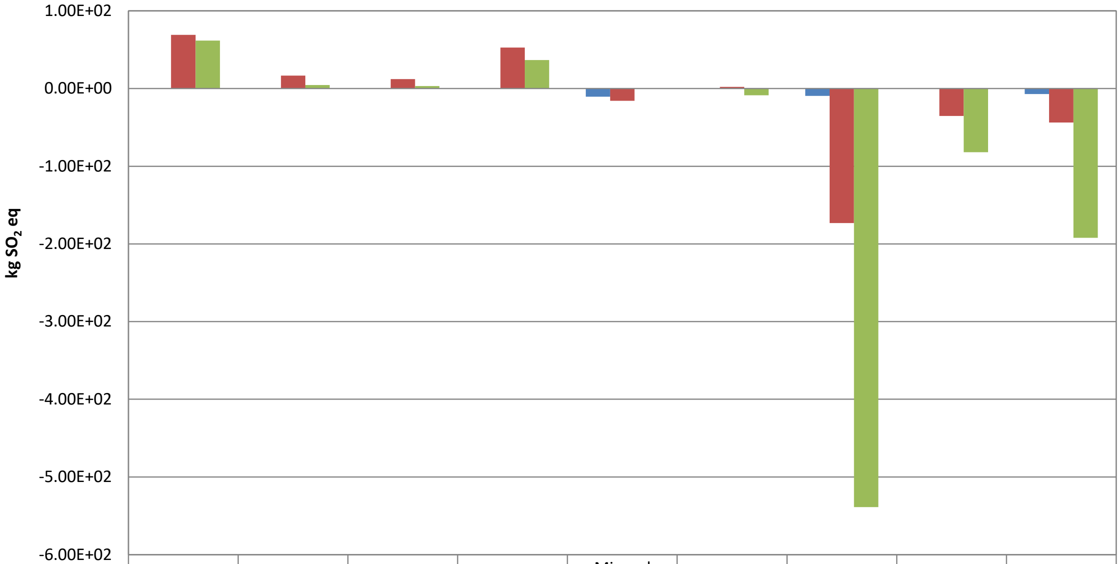
	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
■ Antimony (air)	7.89E+03	1.13E+00	8.15E-01	3.88E+00	-1.31E+01	-2.74E+02	-2.52E+02	-1.18E+01	-1.13E+02
■ Benzene (air)	4.99E+02	1.13E+01	8.19E+00	7.57E+01	1.02E+01	-8.20E+01	-5.80E+04	-5.89E+01	-3.48E+02
■ Benzene (water)	7.64E+01	4.92E+00	3.56E+00	1.50E+01	3.75E-01	-9.76E-01	3.18E+03	2.03E+00	-1.37E+02
■ Benzene, hexachloro- (air)	6.56E-03	3.37E-04	2.44E-04	9.53E-01	-1.75E-03	-1.97E-02	1.16E+04	2.28E-02	6.82E-01
■ Chromium VI (air)	6.57E+01	2.91E+00	2.11E+00	6.99E+01	-5.29E+00	-5.02E+01	5.74E+03	-7.47E+01	-2.48E+02
■ Copper (air)	2.64E+03	6.04E+00	4.37E+00	1.92E+01	-3.65E+00	-9.76E+01	-2.72E+02	-1.04E+01	-5.24E+01
■ Ethylene oxide (air)	2.45E+03	8.12E-03	5.88E-03	2.72E-02	-2.55E-03	-8.17E-03	-5.73E+00	-1.40E+02	-9.49E-02
■ Hydrogen fluoride (air)	6.46E+01	3.36E+00	2.44E+00	1.34E+02	-7.67E+01	-7.45E+01	-2.94E+03	-2.60E+02	-1.66E+03
■ Mercury (air)	1.35E+00	6.66E-02	4.83E-02	2.46E+00	-1.98E-02	-2.47E-01	2.40E+03	-1.54E+01	-1.10E+00
■ Selenium (air)	53.636061	1.38E+00	9.96E-01	1.60E+01	-4.86E-01	-8.84E+00	-9.44E+01	-2.54E+01	-1.00E+04

Figure A4.3. Contribution analysis for the impact category “Abiotic Depletion (fossil fuels)” for the C&DW management system in the base case scenario.



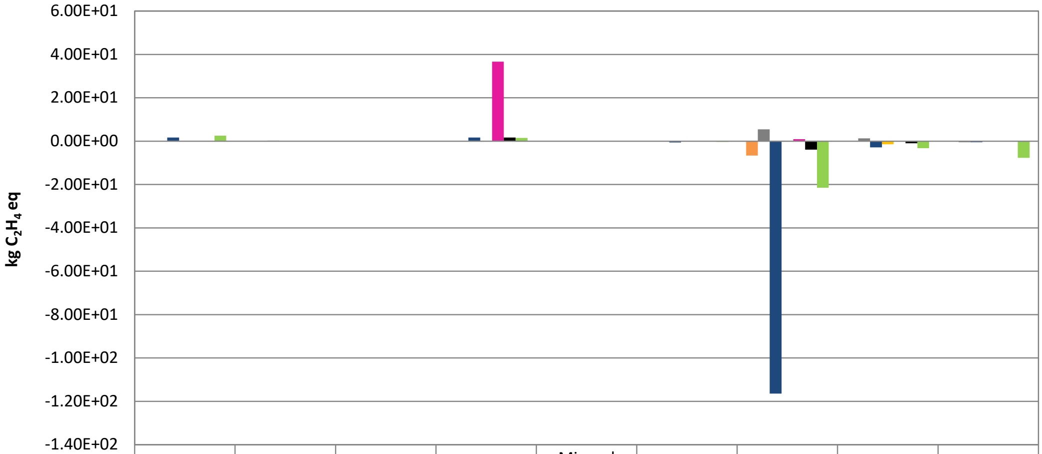
	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
■ Coal, hard	7.91E+03	3.87E+02	2.80E+02	1.62E+04	-5.81E+02	-8.95E+03	-1.45E+06	-6.60E+04	-2.66E+04
■ Gas, coal mining/m³	1.46E+02	7.13E+00	5.16E+00	3.02E+02	-1.22E+01	-1.68E+02	-2.66E+04	-2.27E+02	-5.00E+02
■ Gas, natural/m³	2.97E+04	1.87E+03	1.35E+03	1.28E+04	1.01E+03	-4.01E+03	3.29E+05	-5.09E+05	-1.62E+05
■ Oil, crude	6.43E+05	4.14E+04	3.00E+04	1.22E+05	5.52E+03	-4.26E+03	-1.54E+05	-6.57E+05	-1.80E+05

Figure A4.4. Contribution analysis for the impact category “Acidification” for the C&DW management system in the base case scenario.



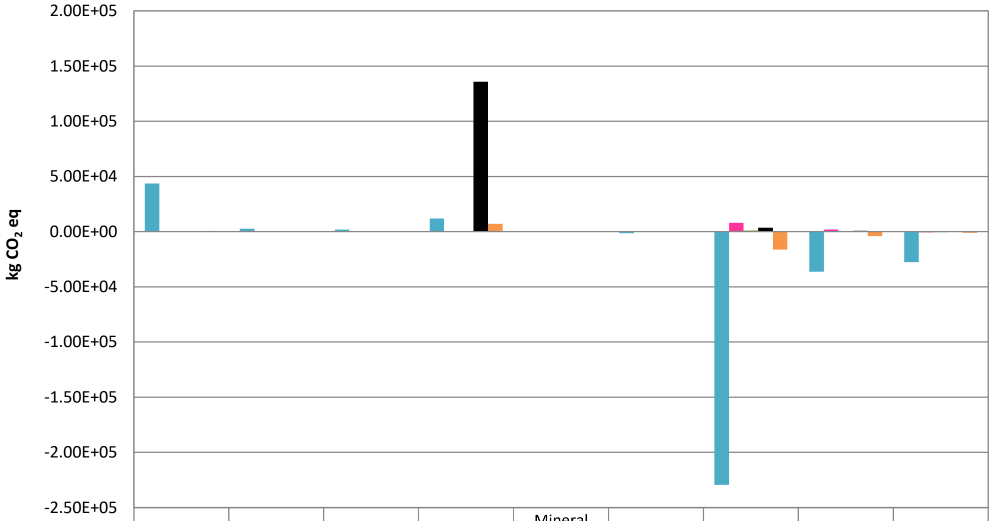
	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
🟦 Ammonia (air)	4.21E-01	2.90E-02	2.10E-02	5.12E-01	-1.05E+01	-1.05E-01	-9.32E+00	6.33E-01	-7.04E+00
🟥 Nitrogen oxides (air)	6.93E+01	1.67E+01	1.21E+01	5.28E+01	-1.56E+01	2.08E+00	-1.73E+02	-3.53E+01	-4.36E+01
🟩 Sulfur dioxide (air)	6.18E+01	4.48E+00	3.25E+00	3.68E+01	2.52E-01	-8.66E+00	-5.39E+02	-8.19E+01	-1.92E+02

Figure A4.5. Contribution analysis for the impact category “Photochemical Oxidation” for the C&DW management system in the base case scenario.



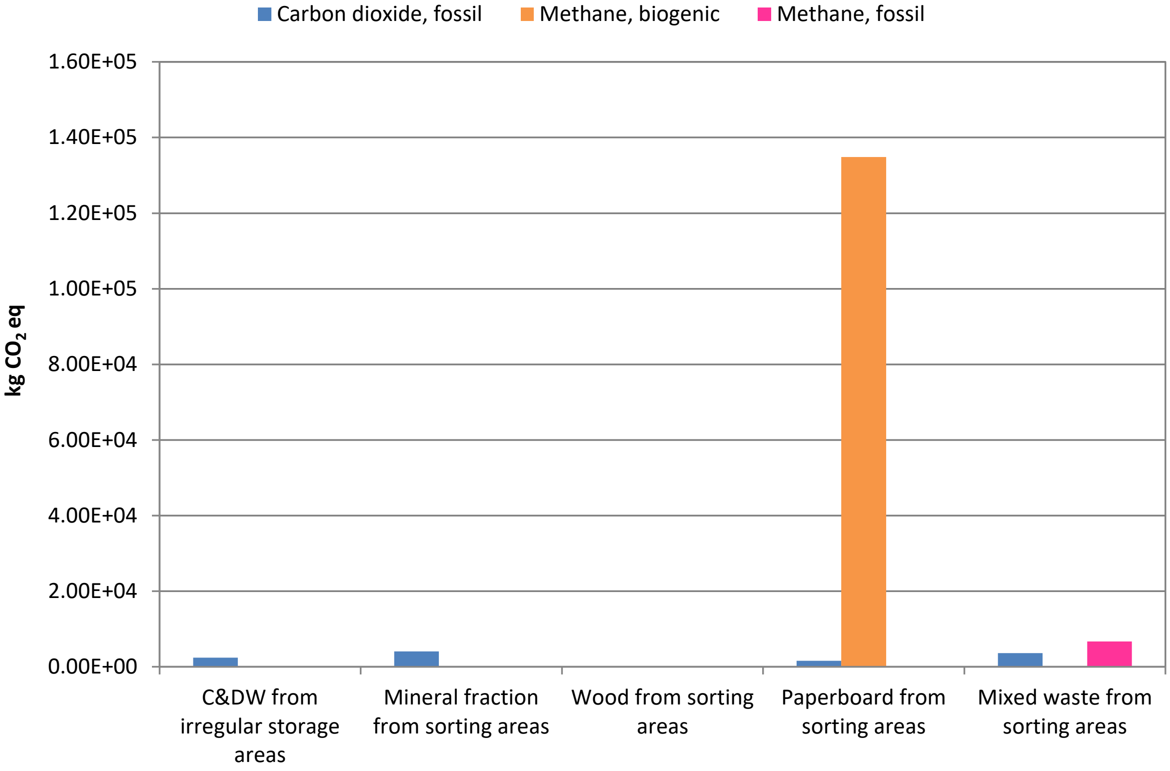
	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
🟧 Benzene (air)	5.73E-02	1.30E-03	9.40E-04	8.69E-03	1.17E-03	-9.41E-03	-6.65E+00	-6.76E-03	-4.00E-02
■ Carbon monoxide, biogenic (air)	7.88E-03	3.38E-04	2.45E-04	1.04E-01	1.18E-01	-8.14E-02	5.45E+00	1.26E+00	-4.87E-01
🟦 Carbon monoxide, fossil (air)	1.63E+00	2.36E-01	1.71E-01	1.66E+00	-1.86E-01	-6.03E-01	-1.16E+02	-2.91E+00	-5.15E-01
🟨 Ethene (air)	4.90E-02	2.80E-03	2.03E-03	4.73E-02	5.05E-04	-3.44E-03	-6.86E-02	-1.43E+00	-5.92E-02
🟪 Methane, biogenic (air)	9.31E-04	5.21E-05	3.77E-05	3.66E+01	2.00E-02	2.05E-02	9.38E-01	1.93E-01	-5.97E-02
⬛ Methane, fossil (air)	1.56E-01	1.03E-02	7.49E-03	1.68E+00	-9.55E-05	-2.92E-02	-3.90E+00	-9.88E-01	-2.50E-01
🟩 Sulfur dioxide (air)	2.47E+00	1.79E-01	1.30E-01	1.47E+00	1.01E-02	-3.46E-01	-2.16E+01	-3.28E+00	-7.68E+00

Figure A4.6. Contribution analysis for the impact category "Global Warming" for the C&DW management system in the base case scenario.



	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
■ Carbon dioxide, fossil (air)	4.37E+04	2.69E+03	1.95E+03	1.19E+04	3.44E+02	-1.36E+03	-2.30E+05	-3.63E+04	-2.76E+04
■ Carbon dioxide, land transformation (air)	2.69E+00	1.49E-01	1.08E-01	1.47E+01	1.73E+02	1.39E+02	8.05E+03	1.88E+03	-6.38E+02
■ Dinitrogen monoxide (air)	2.81E+02	2.78E+01	2.01E+01	2.97E+02	-1.95E+02	-5.91E-01	1.20E+03	2.24E+02	-4.83E+02
■ Methane, biogenic (air)	3.45E+00	1.93E-01	1.40E-01	1.36E+05	7.43E+01	7.61E+01	3.48E+03	7.17E+02	-2.21E+02
■ Methane, fossil (air)	6.51E+02	4.31E+01	3.12E+01	7.01E+03	-3.98E-01	-1.22E+02	-1.62E+04	-4.12E+03	-1.04E+03

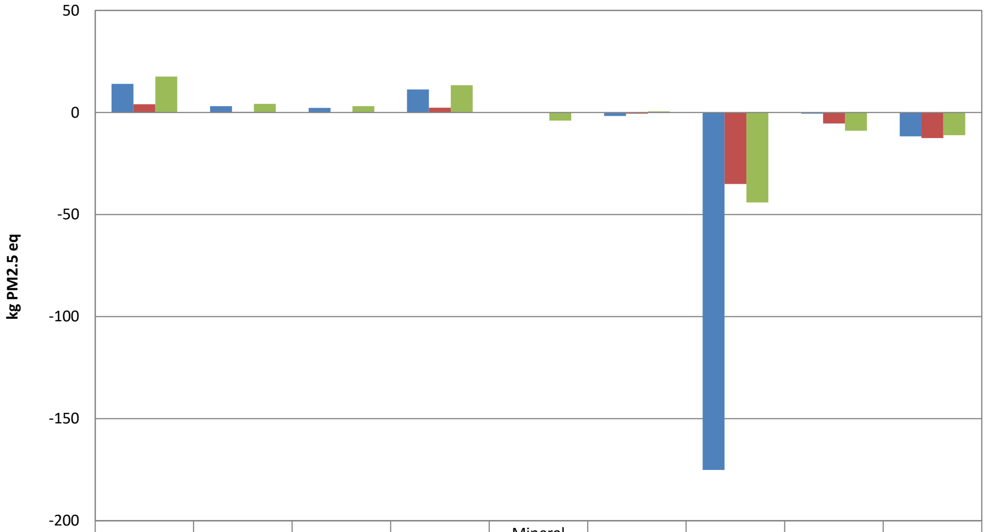
Figure A4.7. Contribution analysis for the impact category "Global Warming" related to the C&DW landfilling in the base case scenario.



APPENDIX A5 – LIFE CYCLE IMPACT ASSESSMENT DATA: IMPACT 2002+ V2.12 METHODOLOGY

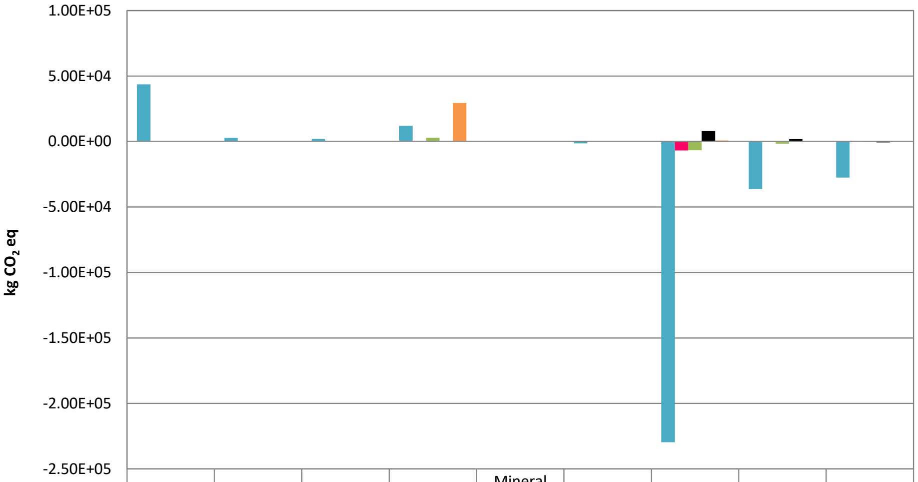
This appendix reports supplementary data of life cycle impact assessment obtained by using the Impact 2002+ v2.12 methodology.

Figure A5.1. Contribution analysis for the impact category "Respiratory Inorganics" for the C&DW management system in the base case scenario.



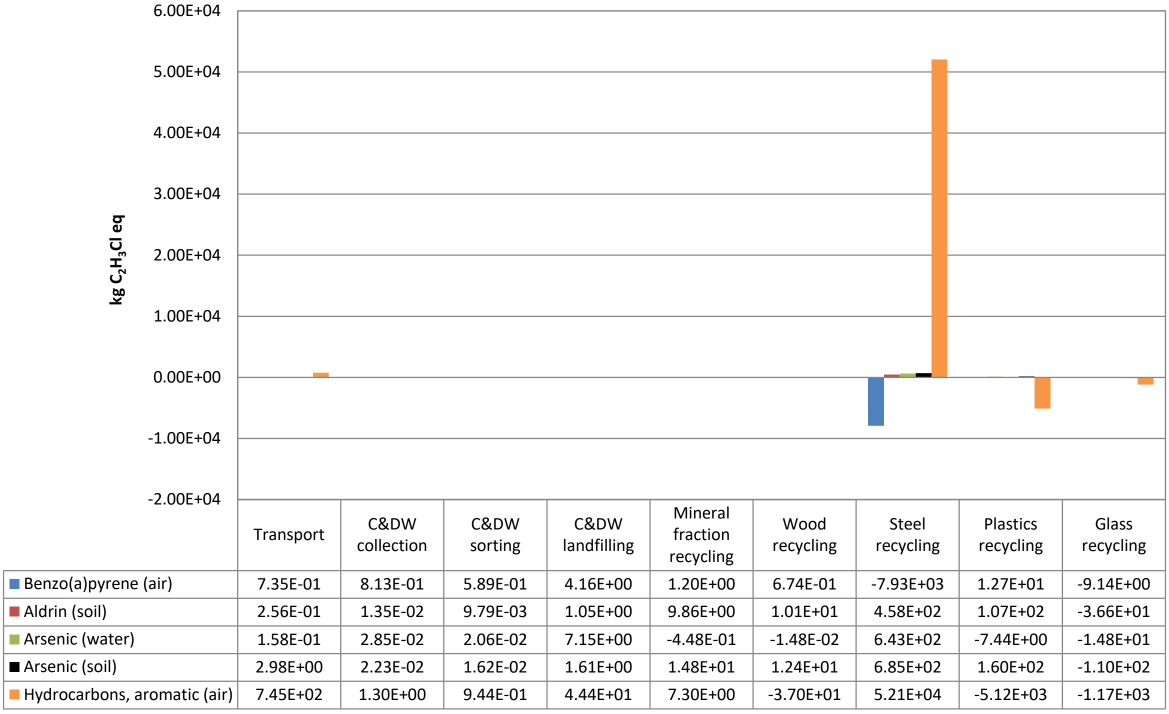
	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
🟦 Particulates, < 2.5 um (air)	14.03	3.07	2.22	11.26	0.05	-1.72	-175.18	-0.59	-11.67
🟥 Sulfur dioxide (air)	4.02	0.29	0.21	2.38	0.02	-0.56	-35.03	-5.32	-12.48
🟩 Nitrogen oxides (air)	17.64	4.26	3.09	13.41	-3.97	0.53	-44.06	-8.98	-11.11

Figure A5.2. Contribution analysis for the impact category "Global Warming" for the C&DW management system in the base case scenario.



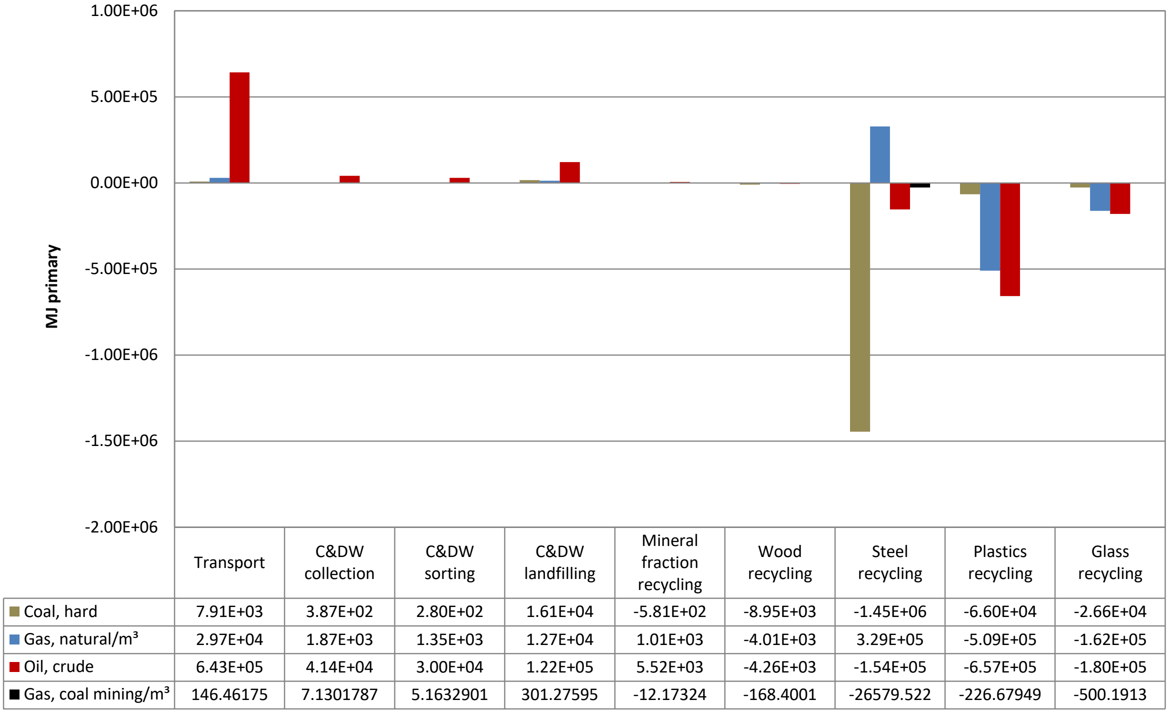
	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
🟦 Carbon dioxide, fossil (air)	4.37E+04	2.69E+03	1.95E+03	1.19E+04	3.44E+02	-1.36E+03	-2.30E+05	-3.63E+04	-2.76E+04
🟥 Carbon monoxide, fossil (air)	9.46E+01	1.37E+01	9.93E+00	9.63E+01	-1.08E+01	-3.50E+01	-6.77E+03	-1.69E+02	-2.99E+01
🟩 Methane, fossil (air)	2.70E+02	1.78E+01	1.29E+01	2.89E+03	-1.65E-01	-5.03E+01	-6.72E+03	-1.70E+03	-4.31E+02
■ Carbon dioxide, land transformation (air)	2.69E+00	1.49E-01	1.08E-01	1.47E+01	1.73E+02	1.39E+02	8.05E+03	1.88E+03	-6.38E+02
🟧 Methane, biogenic (air)	7.53E-01	4.21E-02	3.05E-02	2.94E+04	1.62E+01	1.66E+01	7.58E+02	1.56E+02	-4.83E+01

Figure A5.3. Contribution analysis for the impact category "Carcinogens" for the C&DW management system in the base case scenario.



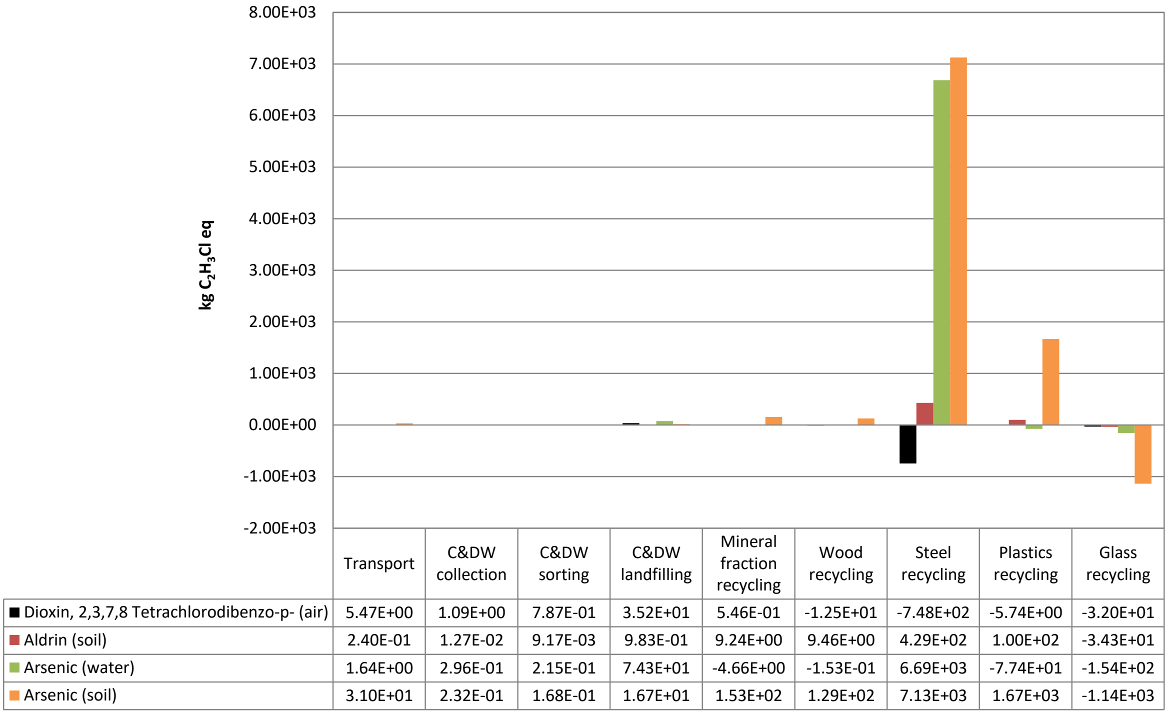
	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
🟦 Benzo(a)pyrene (air)	7.35E-01	8.13E-01	5.89E-01	4.16E+00	1.20E+00	6.74E-01	-7.93E+03	1.27E+01	-9.14E+00
🟥 Aldrin (soil)	2.56E-01	1.35E-02	9.79E-03	1.05E+00	9.86E+00	1.01E+01	4.58E+02	1.07E+02	-3.66E+01
🟩 Arsenic (water)	1.58E-01	2.85E-02	2.06E-02	7.15E+00	-4.48E-01	-1.48E-02	6.43E+02	-7.44E+00	-1.48E+01
■ Arsenic (soil)	2.98E+00	2.23E-02	1.62E-02	1.61E+00	1.48E+01	1.24E+01	6.85E+02	1.60E+02	-1.10E+02
🟧 Hydrocarbons, aromatic (air)	7.45E+02	1.30E+00	9.44E-01	4.44E+01	7.30E+00	-3.70E+01	5.21E+04	-5.12E+03	-1.17E+03

Figure A5.4. Contribution analysis for the impact category "Non-Renewable Energy" for the C&DW management system in the base case scenario.



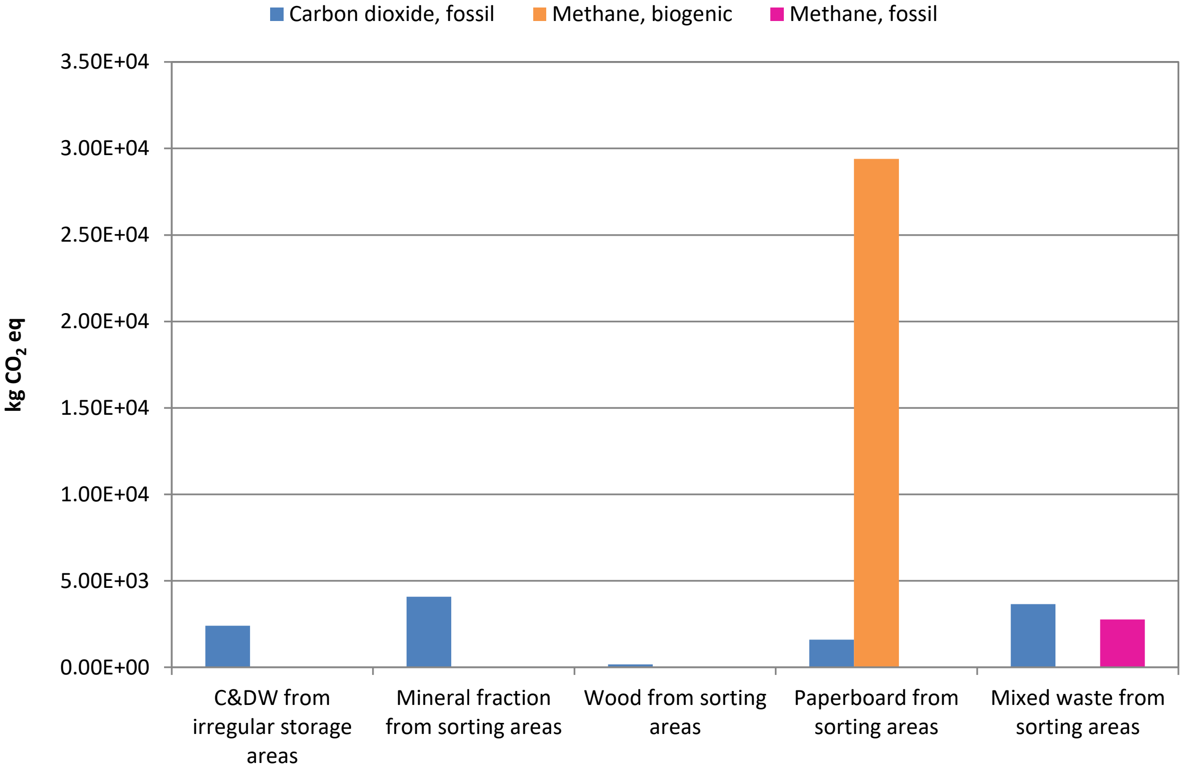
	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
🟫 Coal, hard	7.91E+03	3.87E+02	2.80E+02	1.61E+04	-5.81E+02	-8.95E+03	-1.45E+06	-6.60E+04	-2.66E+04
🟦 Gas, natural/m³	2.97E+04	1.87E+03	1.35E+03	1.27E+04	1.01E+03	-4.01E+03	3.29E+05	-5.09E+05	-1.62E+05
🟥 Oil, crude	6.43E+05	4.14E+04	3.00E+04	1.22E+05	5.52E+03	-4.26E+03	-1.54E+05	-6.57E+05	-1.80E+05
■ Gas, coal mining/m³	146.46175	7.1301787	5.1632901	301.27595	-12.17324	-168.4001	-26579.522	-226.67949	-500.1913

Figure A5.5. Contribution analysis for the impact category "Non-Carcinogens" for the C&DW management system in the base case scenario.



	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
■ Dioxin, 2,3,7,8 Tetrachlorodibenzo-p- (air)	5.47E+00	1.09E+00	7.87E-01	3.52E+01	5.46E-01	-1.25E+01	-7.48E+02	-5.74E+00	-3.20E+01
🟥 Aldrin (soil)	2.40E-01	1.27E-02	9.17E-03	9.83E-01	9.24E+00	9.46E+00	4.29E+02	1.00E+02	-3.43E+01
🟩 Arsenic (water)	1.64E+00	2.96E-01	2.15E-01	7.43E+01	-4.66E+00	-1.53E-01	6.69E+03	-7.74E+01	-1.54E+02
🟧 Arsenic (soil)	3.10E+01	2.32E-01	1.68E-01	1.67E+01	1.53E+02	1.29E+02	7.13E+03	1.67E+03	-1.14E+03

Figure A5.6. Contribution analysis for the impact category “Global Warming” related to the C&DW landfilling in the base case scenario.



APPENDIX A6 – LCI AND LCIA DATA: ALTERNATIVE SCENARIOS (1, 2, 3.1 AND 3.2)

This appendix reports supplementary data of life cycle inventory and life cycle impact assessment of mineral fraction management in the base case and alternative scenarios (1, 2, 3.1 and 3.2).

Figure A6.1. Comparison of the base case scenario when the EURO 4 transportation trucks in all steps of both scenarios are replaced with EURO 3 and EURO 5 transportation trucks. Data obtained by CML baseline.

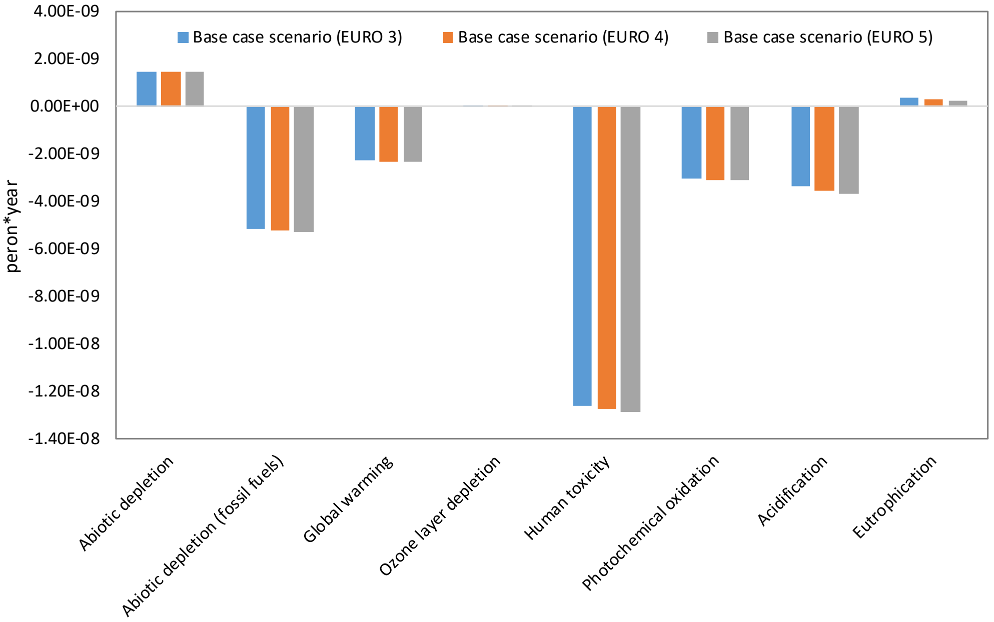


Figure A6.2. Comparison of the base case scenario when the EURO 4 transportation trucks in all steps of both scenarios are replaced with EURO 3 and EURO 5 transportation trucks. Data obtained by Impact 2002+.

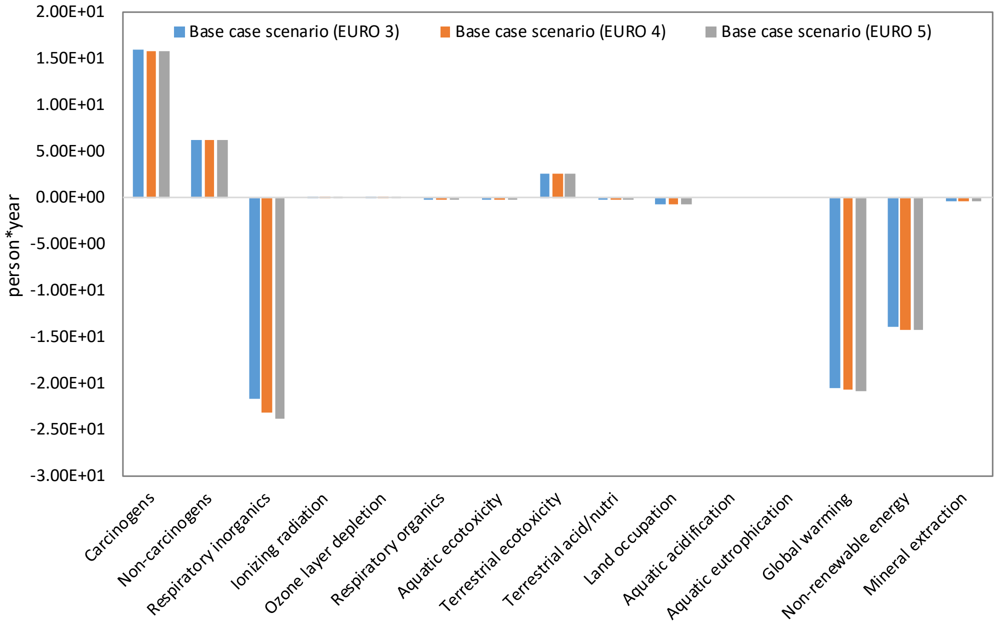


Table A6.1. Main direct burdens of the mineral fraction management in the base case and alternative scenarios 1 and 2.

Life cycle inventory data	**Scenarios**										
	Base case	**1a (20%)**	**1b (40%)**	**1b (60%)**	**1b (80%)**	**1b (100%)**	**2a (20%)**	**2b (40%)**	**2b (60%)**	**2b (80%)**	**2b (100%)**
Transport stages (tkm)											
From sorting areas to inert landfills	18836	0	0	0	0	0	0	0	0	0	0
From sorting areas to recycling facilities	72524	90201	90201	90201	90201	90201	90201	90201	90201	90201	90201
From recycling facilities to inert landfills	454	467	933	1400	1866	2333	467	933	1400	1866	2333
Total (tkm)	**91814**	**90668**	**91134**	**91601**	**92067**	**92534**	**90668**	**91134**	**91601**	**92067**	**92534**
Recycling processes (direct burdens)											
Diesel consumption (L)	655	781	1562	2343	3124	3905	584	1168	1752	2336	2920
Electricity consumption (kWh)	3687	4433	8865	13298	17730	22163	3991	7982	11973	15963	19954
Inert landfilling (t)											
Mineral fraction from sorting areas	1651	0	0	0	0	0	0	0	0	0	0
Process losses from recycling process	65	81	163	244	325	406	81	163	244	325	406
Total (t)	**1716**	**81**	**163**	**244**	**325**	**406**	**81**	**163**	**244**	**325**	**406**
Mineral fraction storage (t)	**5180**	**6501**	**4876**	**3250**	**1625**	**0**	**6501**	**4876**	**3250**	**1625**	**0**

Table A6.2. Main avoided burdens of the mineral fraction management in the base case and alternative scenarios 1 and 2.

Life cycle inventory data	**Scenarios**										
	Base case	**1a (20%)**	**1b (40%)**	**1b (60%)**	**1b (80%)**	**1b (100%)**	**2a (20%)**	**2b (40%)**	**2b (60%)**	**2b (80%)**	**2b (100%)**
Natural aggregate production (avoided burdens)											
Diesel consumption (L)	530	649	1299	1948	2598	3247	548	1096	1644	2192	2740
Electricity consumption (kWh)	1377	1951	3903	5854	7805	9757	3109	6217	9326	12434	15543

Table A6.3. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to inert landfill or recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the base case scenario.

Municipalities	**Sorting area to inert landfill**			**Sorting area to recycling facility**			**Recycling facility to inert landfill**		
	Mineral fraction (t)	**Distance (km)**	**tkm**	**Mineral fraction (t)**	**Distance (km)**	**tkm**	**Process losses (t)**	**Distance (km)**	**tkm**
Atibaia[1]	-	-	-	435	0	0	4	57	248
Campinas[2]	-	-	-	3824	13	49712	38	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	1	0	0
Hortolândia	-	-	-	261	8	2088	3	28	73
Indaiatuba	304	6	1824	-	-	-	-	-	-
Jundiaí[2]	-	-	-	695	6	4170	7	0	0
Limeira	860	12	10320	-	-	-	-	-	-
Nova Odessa	61	19	1159	-	-	-	-	-	-
Piracicaba	-	-	-	869	18	15642	9	10	87
Rio Claro	243	18	4374	-	-	-	-	-	-
Salto	122	6	732	-	-	-	-	-	-
Santa Bárbara	61	7	427	-	-	-	-	-	-
Sumaré	-	-	-	304	3	912	3	15	46
Total	**1651**	**68**	**18836**	**6475**	**48**	**72524**	**65**	**110**	**454**

Note: [1]The recycling facility is located in the same area of the sorting area. [2]The recycling facility is located in the same area of the inert landfill. [3]The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.4. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the alternative scenarios 1a (20%) and 2a (20%).

Municipalities	**Sorting area to inert landfill**			**Sorting area to recycling facility**			**Recycling facility to inert landfill**		
	Mineral fraction (t)	**Distance (km)**	**tkm**	**Mineral fraction (t)**	**Distance (km)**	**tkm**	**Process losses (t)**	**Distance (km)**	**tkm**
Atibaia[1]	-	-	-	435	0	0	4	57	248
Campinas[2]	-	-	-	3824	13	49712	38	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	1	0	0
Hortolândia	-	-	-	261	8	2088	3	28	73
Indaiatuba[2]	-	-	-	304	6	1824	3	0	0
Jundiaí[2]	-	-	-	695	6	4170	7	0	0
Limeira[2]	-	-	-	860	12	10320	9	0	0
Nova Odessa[1]	-	-	-	61	0	0	1	21	13
Piracicaba	-	-	-	869	18	15642	9	10	87
Rio Claro[2]	-	-	-	243	18	4374	2	0	0
Salto[2]	-	-	-	122	6	732	1	0	0
Santa Bárbara[2]	-	-	-	61	7	427	1	0	0
Sumaré	-	-	-	304	3	912	3	15	46
Total	**0**	**0**	**0**	**8126**	**97**	**90201**	**81**	**131**	**467**

Note: [1]The recycling facility is located in the same area of the sorting area. [2]The recycling facility is located in the same area of the inert landfill. [3]The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.5. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the alternative scenarios 1b (40%) and 2b (40%).

Municipalities	**Sorting area to inert landfill**			**Sorting area to recycling facility**			**Recycling facility to inert landfill**		
	Mineral fraction (t)	**Distance (km)**	**tkm**	**Mineral fraction (t)**	**Distance (km)**	**tkm**	**Process losses (t)**	**Distance (km)**	**tkm**
Atibaia[1]	-	-	-	435	0	0	9	57	496
Campinas[2]	-	-	-	3824	13	49712	76	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	2	0	0
Hortolândia	-	-	-	261	8	2088	5	28	146
Indaiatuba[2]	-	-	-	304	6	1824	6	0	0
Jundiaí[2]	-	-	-	695	6	4170	14	0	0
Limeira[2]	-	-	-	860	12	10320	17	0	0
Nova Odessa[1]	-	-	-	61	0	0	1	21	26
Piracicaba	-	-	-	869	18	15642	17	10	174
Rio Claro[2]	-	-	-	243	18	4374	5	0	0
Salto[2]	-	-	-	122	6	732	2	0	0
Santa Bárbara[2]	-	-	-	61	7	427	1	0	0
Sumaré	-	-	-	304	3	912	6	15	91
Total	**0**	**0**	**0**	**8126**	**97**	**90201**	**163**	**131**	**933**

Note: [1]The recycling facility is located in the same area of the sorting area. [2]The recycling facility is located in the same area of the inert landfill. [3]The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.6. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the alternative scenarios 1b (60%) and 2b (60%).

Municipalities	**Sorting area to inert landfill**			**Sorting area to recycling facility**			**Recycling facility to inert landfill**		
	Mineral fraction (t)	**Distance (km)**	**tkm**	**Mineral fraction (t)**	**Distance (km)**	**tkm**	**Process losses (t)**	**Distance (km)**	**tkm**
Atibaia[1]	-	-	-	435	0	0	13	57	744
Campinas[2]	-	-	-	3824	13	49712	115	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	3	0	0
Hortolândia	-	-	-	261	8	2088	8	28	219
Indaiatuba[2]	-	-	-	304	6	1824	9	0	0
Jundiaí[2]	-	-	-	695	6	4170	21	0	0
Limeira[2]	-	-	-	860	12	10320	26	0	0
Nova Odessa[1]	-	-	-	61	0	0	2	21	39
Piracicaba	-	-	-	869	18	15642	26	10	261
Rio Claro[2]	-	-	-	243	18	4374	7	0	0
Salto[2]	-	-	-	122	6	732	4	0	0
Santa Bárbara[2]	-	-	-	61	7	427	2	0	0
Sumaré	-	-	-	304	3	912	9	15	137
Total	**0**	**0**	**0**	**8126**	**97**	**90201**	**244**	**131**	**1400**

Note: [1]The recycling facility is located in the same area of the sorting area. [2]The recycling facility is located in the same area of the inert landfill. [3]The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.7. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the alternative scenarios 1b (80%) and 2b (80%).

Municipalities	**Sorting area to inert landfill**			**Sorting area to recycling facility**			**Recycling facility to inert landfill**		
	Mineral fraction (t)	**Distance (km)**	**tkm**	**Mineral fraction (t)**	**Distance (km)**	**tkm**	**Process losses (t)**	**Distance (km)**	**tkm**
Atibaia[1]	-	-	-	435	0	0	17	57	992
Campinas[2]	-	-	-	3824	13	49712	153	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	3	0	0
Hortolândia	-	-	-	261	8	2088	10	28	292
Indaiatuba[2]	-	-	-	304	6	1824	12	0	0
Jundiaí[2]	-	-	-	695	6	4170	28	0	0
Limeira[2]	-	-	-	860	12	10320	34	0	0
Nova Odessa[1]	-	-	-	61	0	0	2	21	52
Piracicaba	-	-	-	869	18	15642	35	10	348
Rio Claro[2]	-	-	-	243	18	4374	10	0	0
Salto[2]	-	-	-	122	6	732	5	0	0
Santa Bárbara[2]	-	-	-	61	7	427	2	0	0
Sumaré	-	-	-	304	3	912	12	15	182
Total	**0**	**0**	**0**	**8126**	**97**	**90201**	**325**	**131**	**1866**

Note: [1] The recycling facility is located in the same area of the sorting area. [2] The recycling facility is located in the same area of the inert landfill. [3] The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.8. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the alternative scenarios 1b (100%) and 2b (100%).

Municipalities	**Sorting area to inert landfill**			**Sorting area to recycling facility**			**Recycling facility to inert landfill**		
	Mineral fraction (t)	**Distance (km)**	**tkm**	**Mineral fraction (t)**	**Distance (km)**	**tkm**	**Process losses (t)**	**Distance (km)**	**tkm**
Atibaia[1]	-	-	-	435	0	0	22	57	1240
Campinas[2]	-	-	-	3824	13	49712	191	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	4	0	0
Hortolândia	-	-	-	261	8	2088	13	28	365
Indaiatuba[2]	-	-	-	304	6	1824	15	0	0
Jundiaí[2]	-	-	-	695	6	4170	35	0	0
Limeira[2]	-	-	-	860	12	10320	43	0	0
Nova Odessa[1]	-	-	-	61	0	0	3	21	65
Piracicaba	-	-	-	869	18	15642	43	10	435
Rio Claro[2]	-	-	-	243	18	4374	12	0	0
Salto[2]	-	-	-	122	6	732	6	0	0
Santa Bárbara[2]	-	-	-	61	7	427	3	0	0
Sumaré	-	-	-	304	3	912	15	15	228
Total	**0**	**0**	**0**	**8126**	**97**	**90201**	**406**	**131**	**2333**

Note: [1] The recycling facility is located in the same area of the sorting area. [2] The recycling facility is located in the same area of the inert landfill. [3] The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.9. Data about the quantities (in tons) of mineral fraction landfilled, recycled and stored in the base case and alternative scenarios 1 and 2.

Scenarios and Recycling rate	Inert landfilling	Mineral fraction recycling	Recycled aggregates produced	Process Losses[1]	Mineral fraction stored
Base case (20%)	1651	1295	1230	65	5180
1a (20%)	0	1625	1544	81	6501
1b (40%)	0	3250	3088	163	4876
1b (60%)	0	4876	4632	244	3250
1b (80%)	0	6501	6176	325	1625
1b (100%)	0	8126	7720	406	0
2a (20%)	0	1625	1544	81	6501
2b (40%)	0	3250	3088	163	4876
2b (60%)	0	4876	4632	244	3250
2b (80%)	0	6501	6176	325	1625
2b (100%)	0	8126	7720	406	0

Note: [1] This material is disposed of in an inert lanfill.

Table A6.10. Quantity (in tons) and types of recycled aggregates produced in the base case and alternative scenarios 1 and 2.

Scenarios and Recycling rate	Excavated soil	Fine recycled aggregate	Coarse recycled aggregate - Type A	Coarse recycled aggregate - Type B	Total
Base case (20%)	418	62	172	578	1230
1a (20%)	494	93	278	679	1544
1b (40%)	988	185	556	1359	3088
1b (60%)	1482	278	834	2038	4632
1b (80%)	1976	371	1112	2717	6176
1b (100%)	2470	463	1390	3397	7720
2a (20%)	309	154	602	479	1544
2b (40%)	618	309	1204	957	3088
2b (60%)	926	463	1806	1436	4632
2b (80%)	1235	618	2409	1914	6176
2b (100%)	1544	772	3011	2393	7720

Table A6.11. Total consumption of diesel (D) in liter and electricity (E) in kWh used in the production of the recycled aggregates in the base case and alternative scenarios 1 and 2.

Municipalities	**Base case**		**1a (20%)**		**1b (40%)**		**1b (60%)**		**1b (80%)**		**1b (100%)**		**2a (20%)**		**2b (40%)**		**2b (60%)**		**2b (80%)**		**2b (100%)**	
	D	**E**	**D**	**E**	**D**	**E**	**D**	**E**	**D**	**E**	**D**	**E**	**D**	**E**	**D**	**E**	**D**	**E**	**D**	**E**	**D**	**E**
Atibaia	30	77	30	77	61	153	91	230	122	306	152	383	30	221	61	442	91	663	122	884	152	1105
Campinas	467	2463	467	2463	933	4925	1400	7388	1866	9851	2333	12313	268	1943	535	3885	803	5828	1071	7770	1338	9713
Cosmópolis	11	0	11	0	22	0	33	0	44	0	55	0	11	0	22	0	33	0	44	0	55	0
Hortolândia	18	153	18	153	37	307	55	460	73	614	91	767	18	133	37	265	55	398	73	530	91	663
Indaiatuba	0	0	21	154	43	309	64	463	85	618	106	772	21	154	43	309	64	463	85	618	106	772
Jundiaí	49	353	49	353	97	706	146	1059	195	1412	243	1765	49	353	97	706	146	1059	195	1412	243	1765
Limeira	0	0	60	437	120	874	181	1311	241	1748	301	2184	60	437	120	874	181	1311	241	1748	301	2184
Nova Odessa	0	0	8	0	15	0	23	0	31	0	38	0	8	0	15	0	23	0	31	0	38	0
Piracicaba	59	487	59	487	118	973	177	1460	236	1947	295	2433	61	441	122	883	182	1324	243	1766	304	2207
Rio Claro	0	0	17	123	34	247	51	370	68	494	85	617	17	123	34	247	51	370	68	494	85	617
Salto	0	0	15	0	31	0	46	0	61	0	77	0	15	0	31	0	46	0	61	0	77	0
Santa Bárbara	0	0	4	31	9	62	13	93	17	124	21	155	4	31	9	62	13	93	17	124	21	155
Sumaré	21	154	21	154	43	309	64	463	85	618	106	772	21	154	43	309	64	463	85	618	106	772
Total	**655**	**3687**	**781**	**4433**	**1562**	**8865**	**2343**	**13298**	**3124**	**17730**	**3905**	**22163**	**584**	**3991**	**1168**	**7982**	**1752**	**11973**	**2336**	**15963**	**2920**	**19954**

Figure A6.3. Contribution analysis for the impact category "Acidification" for the C&DW management system in the base case and alternative scenarios (CML baseline methodology).

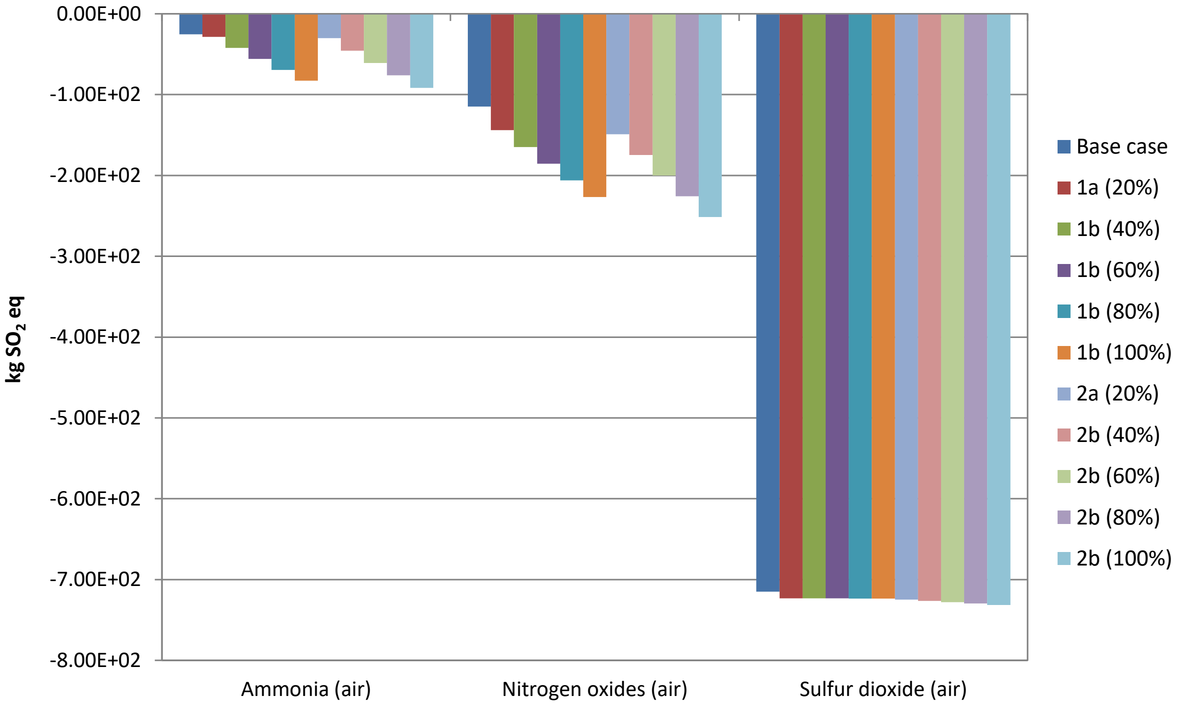


Figure A6.4. Contribution analysis for the impact category "Respiratory Inorganics" for the C&DW management system in the base case and alternative scenarios (Impact 2002+ methodology).

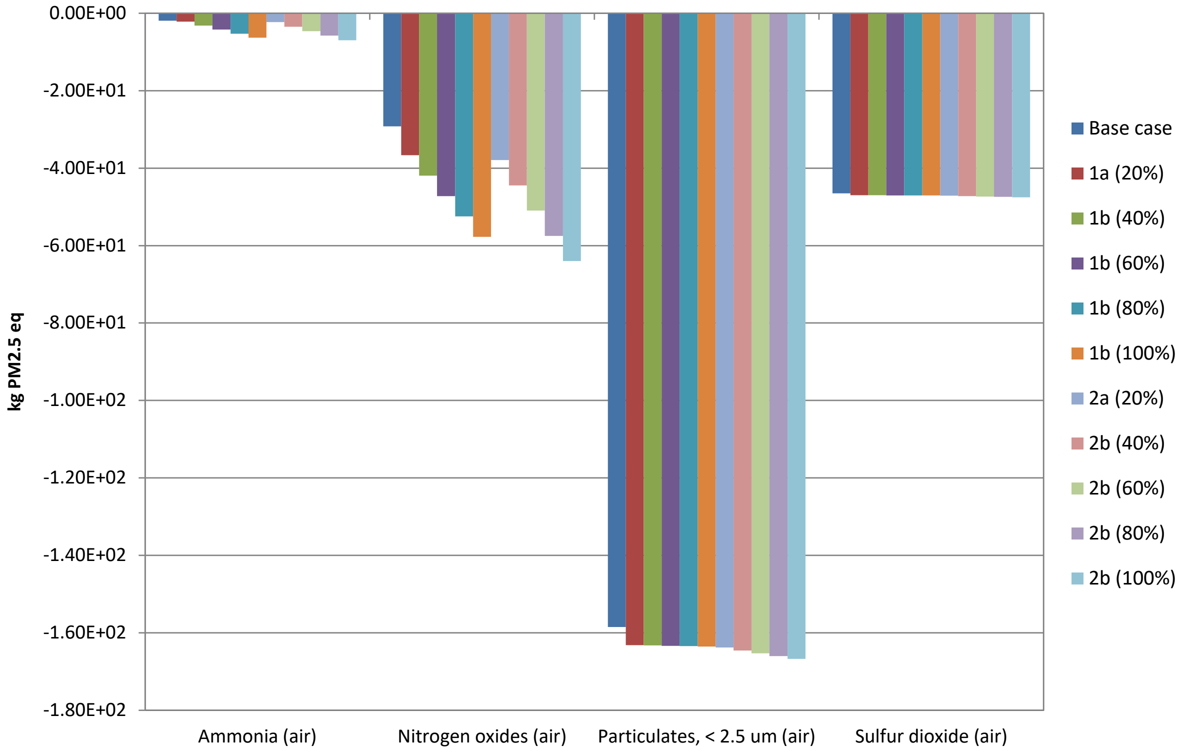


Table A6.12. Main direct burdens of the mineral fraction management in the base case and alternative scenarios 3.1 and 3.2.

Life cycle inventory data	**3.1a (20%)**	**3.1b (40%)**	**3.1b (60%)**	**3.1b (80%)**	**3.1b (100%)**	**3.2a (20%)**	**3.2b (40%)**	**3.2b (60%)**	**3.2b (80%)**	**3.2b (100%)**
Transport stages (tkm)										
From sorting areas to inert landfills	0	0	0	0	0	15069	11302	7534	3767	0
From sorting areas to recycling facilities	167788	167788	167788	167788	167788	91577	110629	129682	148735	167788
From recycling facilities to inert landfills	590	1180	1769	2359	2949	590	1180	1769	2359	2949
Total (tkm)	**168378**	**168968**	**169557**	**170147**	**170737**	**107236**	**123111**	**138985**	**154861**	**170737**
Recycling processes (direct burdens)										
Diesel consumption (L)	784	1569	2353	3138	3922	784	1569	2353	3138	3922
Electricity consumption (kWh)	4624	9248	13873	18497	23121	4624	9248	13873	18497	23121
Inert landfilling (t)										
Mineral fraction from sorting areas	0	0	0	0	0	1321	991	660	330	0
Process losses from recycling	81	163	244	325	406	81	163	244	325	406
Total Inert Landfilling (t)	**81**	**163**	**244**	**325**	**406**	**1402**	**1153**	**904**	**655**	**406**
Mineral fraction storage (t)	**6501**	**4876**	**3250**	**1625**	**0**	**5180**	**3885**	**2590**	**1295**	**0**

Table A6.13. Main avoided burdens of the mineral fraction management in the base case and alternative scenarios 3.1 and 3.2.

Life cycle inventory data	**3.1a (20%)**	**3.1b (40%)**	**3.1b (60%)**	**3.1b (80%)**	**3.1b (100%)**	**3.2a (20%)**	**3.2b (40%)**	**3.2b (60%)**	**3.2b (80%)**	**3.2b (100%)**
Natural aggregate production (avoided burdens)										
Diesel consumption (L)	1225	2450	3675	4900	6125	1225	2450	3675	4900	6125
Electricity consumption (kWh)	1884	3768	5652	7536	9419	1884	3768	5652	7536	9419

Table A6.14. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the alternative scenario 3.1a (20%).

Municipalities	Sorting area to inert landfill			Sorting area to recycling facility			Recycling facility to inert landfill		
	Mineral fraction (t)	Distance (km)	tkm	Mineral fraction (t)	Distance (km)	tkm	Process losses (t)	Distance (km)	tkm
Atibaia[1]	-	-	-	435	0	0	4	57	248
Campinas[2]	-	-	-	3824	13	49712	38	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	1	0	0
Hortolândia	-	-	-	261	8	2088	3	28	73
Indaiatuba[2]	-	-	-	304	40	12190	3	0	0
Jundiaí[2]	-	-	-	695	6	4170	7	0	0
Limeira	-	-	-	860	69	59082	9	10	86
Nova Odessa	-	-	-	61	4	262	1	21	13
Piracicaba	-	-	-	869	18	15642	9	10	87
Rio Claro	-	-	-	243	63	15406	2	10	24
Salto[2]	-	-	-	122	59	7149	1	0	0
Santa Bárbara	-	-	-	61	19	1174	1	21	13
Sumaré	-	-	-	304	3	912	3	15	46
Total	**0**	**0**	**0**	**8126**	**302**	**167788**	**81**	**173**	**590**

Note: [1]The recycling facility is located in the same area of the sorting area. [2]The recycling facility is located in the same area of the inert landfill. [3]The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.15. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the alternative scenario 3.1b (40%).

Municipalities	Sorting area to inert landfill			Sorting area to recycling facility			Recycling facility to inert landfill		
	Mineral fraction (t)	Distance (km)	tkm	Mineral fraction (t)	Distance (km)	tkm	Process losses (t)	Distance (km)	tkm
Atibaia[1]	-	-	-	435	0	0	9	57	496
Campinas[2]	-	-	-	3824	13	49712	76	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	2	0	0
Hortolândia	-	-	-	261	8	2088	5	28	146
Indaiatuba[2]	-	-	-	304	40	12190	6	0	0
Jundiaí[2]	-	-	-	695	6	4170	14	0	0
Limeira	-	-	-	860	69	59082	17	10	172
Nova Odessa	-	-	-	61	4	262	1	21	26
Piracicaba	-	-	-	869	18	15642	17	10	174
Rio Claro	-	-	-	243	63	15406	5	10	49
Salto[2]	-	-	-	122	59	7149	2	0	0
Santa Bárbara	-	-	-	61	19	1174	1	21	26
Sumaré	-	-	-	304	3	912	6	15	91
Total	**0**	**0**	**0**	**8126**	**302**	**167788**	**163**	**173**	**1180**

Note: [1]The recycling facility is located in the same area of the sorting area. [2]The recycling facility is located in the same area of the inert landfill. [3]The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.16. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the alternative scenario 3.1b (60%).

Municipalities	Sorting area to inert landfill			Sorting area to recycling facility			Recycling facility to inert landfill		
	Mineral fraction (t)	Distance (km)	tkm	Mineral fraction (t)	Distance (km)	tkm	Process losses (t)	Distance (km)	tkm
Atibaia[1]	-	-	-	435	0	0	13	57	744
Campinas[2]	-	-	-	3824	13	49712	115	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	3	0	0
Hortolândia	-	-	-	261	8	2088	8	28	219
Indaiatuba[2]	-	-	-	304	40	12190	9	0	0
Jundiaí[2]	-	-	-	695	6	4170	21	0	0
Limeira	-	-	-	860	69	59082	26	10	258
Nova Odessa	-	-	-	61	4	262	2	21	39
Piracicaba	-	-	-	869	18	15642	26	10	261
Rio Claro	-	-	-	243	63	15406	7	10	73
Salto[2]	-	-	-	122	59	7149	4	0	0
Santa Bárbara	-	-	-	61	19	1174	2	21	39
Sumaré	-	-	-	304	3	912	9	15	137
Total	**0**	**0**	**0**	**8126**	**302**	**167788**	**244**	**173**	**1769**

Note: [1] The recycling facility is located in the same area of the sorting area. [2] The recycling facility is located in the same area of the inert landfill. [3] The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.17. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the alternative scenario 3.1b (80%).

Municipalities	Sorting area to inert landfill			Sorting area to recycling facility			Recycling facility to inert landfill		
	Mineral fraction (t)	Distance (km)	tkm	Mineral fraction (t)	Distance (km)	tkm	Process losses (t)	Distance (km)	tkm
Atibaia[1]	-	-	-	435	0	0	17	57	992
Campinas[2]	-	-	-	3824	13	49712	153	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	3	0	0
Hortolândia	-	-	-	261	8	2088	10	28	292
Indaiatuba[2]	-	-	-	304	40	12190	12	0	0
Jundiaí[2]	-	-	-	695	6	4170	28	0	0
Limeira	-	-	-	860	69	59082	34	10	344
Nova Odessa	-	-	-	61	4	262	2	21	52
Piracicaba	-	-	-	869	18	15642	35	10	348
Rio Claro	-	-	-	243	63	15406	10	10	97
Salto[2]	-	-	-	122	59	7149	5	0	0
Santa Bárbara	-	-	-	61	19	1174	2	21	52
Sumaré	-	-	-	304	3	912	12	15	182
Total	**0**	**0**	**0**	**8126**	**302**	**167788**	**325**	**173**	**2359**

Note: [1] The recycling facility is located in the same area of the sorting area. [2] The recycling facility is located in the same area of the inert landfill. [3] The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.18. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the alternative scenario 3.1b (100%).

Municipalities	**Sorting area to inert landfill**			**Sorting area to recycling facility**			**Recycling facility to inert landfill**		
	Mineral fraction (t)	**Distance (km)**	**tkm**	**Mineral fraction (t)**	**Distance (km)**	**tkm**	**Process losses (t)**	**Distance (km)**	**tkm**
Atibaia[1]	-	-	-	435	0	0	22	57	1240
Campinas[2]	-	-	-	3824	13	49712	191	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	4	0	0
Hortolândia	-	-	-	261	8	2088	13	28	365
Indaiatuba[2]	-	-	-	304	40	12190	15	0	0
Jundiaí[2]	-	-	-	695	6	4170	35	0	0
Limeira	-	-	-	860	69	59082	43	10	430
Nova Odessa	-	-	-	61	4	262	3	21	65
Piracicaba	-	-	-	869	18	15642	43	10	435
Rio Claro	-	-	-	243	63	15406	12	10	122
Salto[2]	-	-	-	122	59	7149	6	0	0
Santa Bárbara	-	-	-	61	19	1174	3	21	65
Sumaré	-	-	-	304	3	912	15	15	228
Total	**0**	**0**	**0**	**8126**	**302**	**167788**	**406**	**173**	**2949**

Note: [1]The recycling facility is located in the same area of the sorting area. [2]The recycling facility is located in the same area of the inert landfill. [3]The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.19. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the alternative scenario 3.2a (20%).

Municipalities	**Sorting area to inert landfill**			**Sorting area to recycling facility**			**Recycling facility to inert landfill**		
	Mineral fraction (t)	**Distance (km)**	**tkm**	**Mineral fraction (t)**	**Distance (km)**	**tkm**	**Process losses (t)**	**Distance (km)**	**tkm**
Atibaia[1]	-	-	-	435	0	0	4	57	248
Campinas[2]	-	-	-	3824	13	49712	38	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	1	0	0
Hortolândia	-	-	-	261	8	2088	3	28	73
Indaiatuba[2]	243	6	1459	61	40	2438	3	0	0
Jundiaí[2]	-	-	-	695	6	4170	7	0	0
Limeira	688	12	8256	172	69	11816	9	10	86
Nova Odessa	49	19	927	12	4	52	1	21	13
Piracicaba	-	-	-	869	18	15642	9	10	87
Rio Claro	194	18	3499	49	63	3081	2	10	24
Salto[2]	98	6	586	24	59	1430	1	0	0
Santa Bárbara	49	7	342	12	19	235	1	21	13
Sumaré	-	-	-	304	3	912	3	15	46
Total	**1321**	**68**	**15069**	**6805**	**302**	**91577**	**81**	**173**	**590**

Note: [1]The recycling facility is located in the same area of the sorting area. [2]The recycling facility is located in the same area of the inert landfill. [3]The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.20. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the alternative scenario 3.2b (40%).

Municipalities	**Sorting area to inert landfill**			**Sorting area to recycling facility**			**Recycling facility to inert landfill**		
	Mineral fraction (t)	**Distance (km)**	**tkm**	**Mineral fraction (t)**	**Distance (km)**	**tkm**	**Process losses (t)**	**Distance (km)**	**tkm**
Atibaia[1]	-	-	-	435	0	0	9	57	496
Campinas[2]	-	-	-	3824	13	49712	76	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	2	0	0
Hortolândia	-	-	-	261	8	2088	5	28	146
Indaiatuba[2]	182	6	1094	122	40	4876	6	0	0
Jundiaí[2]	-	-	-	695	6	4170	14	0	0
Limeira	516	12	6192	344	69	23633	17	10	172
Nova Odessa	37	19	695	24	4	105	1	21	26
Piracicaba	-	-	-	869	18	15642	17	10	174
Rio Claro	146	18	2624	97	63	6162	5	10	49
Salto[2]	73	6	439	49	59	2860	2	0	0
Santa Bárbara	37	7	256	24	19	469	1	21	26
Sumaré	-	-	-	304	3	912	6	15	91
Total	**991**	**68**	**11302**	**7135**	**302**	**110629**	**163**	**173**	**1180**

Note: [1]The recycling facility is located in the same area of the sorting area. [2]The recycling facility is located in the same area of the inert landfill. [3]The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.21. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the alternative scenario 3.2b (60%).

Municipalities	**Sorting area to inert landfill**			**Sorting area to recycling facility**			**Recycling facility to inert landfill**		
	Mineral fraction (t)	**Distance (km)**	**tkm**	**Mineral fraction (t)**	**Distance (km)**	**tkm**	**Process losses (t)**	**Distance (km)**	**tkm**
Atibaia[1]	-	-	-	435	0	0	13	57	744
Campinas[2]	-	-	-	3824	13	49712	115	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	3	0	0
Hortolândia	-	-	-	261	8	2088	8	28	219
Indaiatuba[2]	122	6	730	182	40	7314	9	0	0
Jundiaí[2]	-	-	-	695	6	4170	21	0	0
Limeira	344	12	4128	516	69	35449	26	10	258
Nova Odessa	24	19	464	37	4	157	2	21	39
Piracicaba	-	-	-	869	18	15642	26	10	261
Rio Claro	97	18	1750	146	63	9244	7	10	73
Salto[2]	49	6	293	73	59	4290	4	0	0
Santa Bárbara	24	7	171	37	19	704	2	21	39
Sumaré	-	-	-	304	3	912	9	15	137
Total	**660**	**68**	**7534**	**7466**	**302**	**129682**	**244**	**173**	**1769**

Note: [1]The recycling facility is located in the same area of the sorting area. [2]The recycling facility is located in the same area of the inert landfill. [3]The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.22. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the alternative scenario 3.2b (80%).

Municipality	**Sorting area to inert landfill**			**Sorting area to recycling facility**			**Recycling facility to inert landfill**		
	Mineral fraction (t)	**Distance (km)**	**tkm**	**Mineral fraction (t)**	**Distance (km)**	**tkm**	**Process losses (t)**	**Distance (km)**	**tkm**
Atibaia[1]	-	-	-	435	0	0	17	57	992
Campinas[2]	-	-	-	3824	13	49712	153	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	3	0	0
Hortolândia	-	-	-	261	8	2088	10	28	292
Indaiatuba[2]	61	6	365	243	40	9752	12	0	0
Jundiaí[2]	-	-	-	695	6	4170	28	0	0
Limeira	172	12	2064	688	69	47266	34	10	344
Nova Odessa	12	19	232	49	4	210	2	21	52
Piracicaba	-	-	-	869	18	15642	35	10	348
Rio Claro	49	18	875	194	63	12325	10	10	97
Salto[2]	24	6	146	98	59	5719	5	0	0
Santa Bárbara	12	7	85	49	19	939	2	21	52
Sumaré	-	-	-	304	3	912	12	15	182
Total	**330**	**68**	**3767**	**7796**	**302**	**148735**	**325**	**173**	**2359**

Note: [1]The recycling facility is located in the same area of the sorting area. [2]The recycling facility is located in the same area of the inert landfill. [3]The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.23. Data about the quantity of mineral fraction (t) and transport distances (km) from sorting area to recycling facility, and the quantity of process losses (t) and transport distances (km) from recycling facility to inert landfill in the alternative scenario 3.2b (100%).

Municipality	**Sorting area to inert landfill**			**Sorting area to recycling facility**			**Recycling facility to inert landfill**		
	Mineral fraction (t)	**Distance (km)**	**tkm**	**Mineral fraction (t)**	**Distance (km)**	**tkm**	**Process losses (t)**	**Distance (km)**	**tkm**
Atibaia[1]	-	-	-	435	0	0	22	57	1240
Campinas[2]	-	-	-	3824	13	49712	191	0	0
Cosmópolis[1,3]	-	-	-	87	0	0	4	0	0
Hortolândia	-	-	-	261	8	2088	13	28	365
Indaiatuba[2]	-	-	-	304	40	12190	15	0	0
Jundiaí[2]	-	-	-	695	6	4170	35	0	0
Limeira	-	-	-	860	69	59082	43	10	430
Nova Odessa	-	-	-	61	4	262	3	21	65
Piracicaba	-	-	-	869	18	15642	43	10	435
Rio Claro	-	-	-	243	63	15406	12	10	122
Salto[2]	-	-	-	122	59	7149	6	0	0
Santa Bárbara	-	-	-	61	19	1174	3	21	65
Sumaré	-	-	-	304	3	912	15	15	228
Total	**0**	**0**	**0**	**8126**	**302**	**167788**	**406**	**173**	**2949**

Note: [1]The recycling facility is located in the same area of the sorting area. [2]The recycling facility is located in the same area of the inert landfill. [3]The municipality does not transport the process losses to the inert landfill, and the material remains in the same area of the recycling facility.

Table A6.24. Data about the quantities (in tons) of mineral fraction landfilled, recycled and stored in alternative scenarios 3.1 and 3.2.

Scenarios and Recycling rate	Inert landfilling	Mineral fraction recycling	Recycled aggregates	Process Losses[1]	Mineral fraction stored
3.1a (20%)	0	1625	1544	81	6501
3.1b (40%)	0	3250	3088	163	4876
3.1b (60%)	0	4876	4632	244	3250
3.1b (80%)	0	6501	6176	325	1625
3.1b (100%)	0	8126	7720	406	0
3.2a (20%)	1321	1625	1544	81	5180
3.2b (40%)	991	3250	3088	163	3885
3.2b (60%)	660	4876	4632	244	2590
3.2b (80%)	330	6501	6176	325	1295
3.2b (100%)	0	8126	7720	406	0

Note: [1]This material is disposed of in an inert lanfill.

Table A6.25. Quantity (in tons) and types of recycled aggregates produced in alternative scenarios 3.1 and 3.2.

Scenarios and Recycling rate	Excavated soil	Fine recycled aggregate	Coarse recycled aggregate - Type A	Coarse recycled aggregate - Type B	Total
3.1a (20%)	474	117	229	723	1544
3.1b (40%)	948	234	459	1446	3088
3.1b (60%)	1423	352	688	2169	4632
3.1b (80%)	1897	469	918	2892	6176
3.1b (100%)	2371	586	1147	3615	7720
3.2a (20%)	474	117	229	723	1544
3.2b (40%)	948	234	459	1446	3088
3.2b (60%)	1423	352	688	2169	4632
3.2b (80%)	1897	469	918	2892	6176
3.2b (100%)	2371	586	1147	3615	7720

Table A6.26. Total consumption of diesel (D) in liter and electricity (E) in kWh used in the production of the recycled aggregates in alternative scenarios 3.1 and 3.2.

Municipalities	**3.1a (20%)**		**3.1b (40%)**		**3.1b (60%)**		**3.1b (80%)**		**3.1b (100%)**		**3.2a (20%)**		**3.2b (40%)**		**3.2b (60%)**		**3.2b (80%)**		**3.2b (100%)**	
	D	**E**	**D**	**E**	**D**	**E**	**D**	**E**	**D**	**E**	**D**	**E**	**D**	**E**	**D**	**E**	**D**	**E**	**D**	**E**
Atibaia	30	77	61	153	91	230	122	306	152	383	30	77	61	153	91	230	122	306	152	383
Campinas	467	2463	933	4925	1400	7388	1866	9851	2333	12313	467	2463	933	4925	1400	7388	1866	9851	2333	12313
Cosmópolis	11	0	22	0	33	0	44	0	55	0	11	0	22	0	33	0	44	0	55	0
Hortolândia	18	153	37	307	55	460	73	614	91	767	18	153	37	307	55	460	73	614	91	767
Indaiatuba	37	196	74	392	111	587	148	783	185	979	37	196	74	392	111	587	148	783	185	979
Jundiaí	49	353	97	706	146	1059	195	1412	243	1765	49	353	97	706	146	1059	195	1412	243	1765
Limeira	58	482	117	963	175	1445	234	1926	292	2408	58	482	117	963	175	1445	234	1926	292	2408
Nova Odessa	4	31	9	62	13	93	17	124	21	155	4	31	9	62	13	93	17	124	21	155
Piracicaba	59	487	118	973	177	1460	236	1947	295	2433	59	487	118	973	177	1460	236	1947	295	2433
Rio Claro	17	136	33	272	50	408	66	544	83	680	17	136	33	272	50	408	66	544	83	680
Salto	9	62	17	124	26	186	34	248	43	310	9	62	17	124	26	186	34	248	43	310
Santa Bárbara	4	31	9	62	13	93	17	124	21	155	4	31	9	62	13	93	17	124	21	155
Sumaré	21	154	43	309	64	463	85	618	106	772	21	154	43	309	64	463	85	618	106	772
Total	**784**	**4624**	**1569**	**9248**	**2353**	**13873**	**3138**	**18497**	**3922**	**23121**	**784**	**4624**	**1569**	**9248**	**2353**	**13873**	**3138**	**18497**	**3922**	**23121**

APPENDIX A7 – SENSITIVITY ANALYSIS: VARIATIONS OF THE C&DW COMPOSITION

This appendix reports supplementary data of sensitivity analysis related to the variations in the C&DW composition.

Table A7.1. Variations from +10% to +100% of wood in relation to its weight-percentage in the composition used in the base case scenario.

C&DW composition	**Base case (%)**	**Variation in the weight-percentage of wood**									
		+10%	**+20%**	**+30%**	**+40%**	**+50%**	**+60%**	**+70%**	**+80%**	**+90%**	**+100%**
MixC&DW	**68.80**	**68.43**	**68.06**	**67.69**	**67.32**	**66.95**	**66.58**	**66.21**	**65.84**	**65.47**	**65.10**
Excavated soil	**18.10**	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10
Wood	**3.70**	**4.07**	**4.44**	**4.81**	**5.18**	**5.55**	**5.92**	**6.29**	**6.66**	**7.03**	**7.40**
Gypsum	**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron and steel	**3.20**	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20
Glass	**1.70**	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
Plastics	**1.50**	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Paper/Cardboard	**1.20**	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Mixed waste	**1.80**	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Table A7.2. Addition from +1% to +10% of gypsum in the composition used in the base case scenario.

C&DW composition	**Base case (%)**	**Variation in the weight-percentage of gypsum**									
		+1%	**+2%**	**+3%**	**+4%**	**+5%**	**+6%**	**+7%**	**+8%**	**+9%**	**+10%**
MixC&DW	**68.80**	**67.80**	**66.80**	**65.80**	**64.80**	**63.80**	**62.80**	**61.80**	**60.80**	**59.80**	**58.80**
Excavated soil	**18.10**	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1
Wood	**3.70**	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70
Gypsum	**0.00**	**1.00**	**2.00**	**3.00**	**4.00**	**5.00**	**6.00**	**7.00**	**8.00**	**9.00**	**10.00**
Iron and steel	**3.20**	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20
Glass	**1.70**	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
Plastics	**1.50**	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Paper/Cardboard	**1.20**	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Mixed waste	**1.80**	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Table A7.3. Variations from +10% to +1000% of mixed waste in relation to its weight-percentage in the composition used in the base case scenario.

C&DW composition	**Base case (%)**	**Variation in the weight-percentage of mixed waste**																		
		+10%	**+20%**	**+30%**	**+40%**	**+50%**	**+60%**	**+70%**	**+80%**	**+90%**	**+100%**	**+200%**	**+300%**	**+400%**	**+500%**	**600%**	**+700%**	**+800%**	**+900%**	**+1000%**
MixC&DW	**68.80**	**68.62**	**68.44**	**68.26**	**68.08**	**67.90**	**67.72**	**67.54**	**67.36**	**67.18**	**67.00**	**65.20**	**63.40**	**61.60**	**59.80**	**58.00**	**56.20**	**54.40**	**52.60**	**50.80**
Excavated soil	**18.10**	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10
Wood	**3.70**	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70
Gypsum	**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron and steel	**3.20**	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20
Glass	**1.70**	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
Plastics	**1.50**	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Paper/Cardboard	**1.20**	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Mixed waste	**1.80**	**1.98**	**2.16**	**2.34**	**2.52**	**2.70**	**2.88**	**3.06**	**3.24**	**3.42**	**3.60**	**5.40**	**7.20**	**9.00**	**10.80**	**12.60**	**14.40**	**16.20**	**18.00**	**19.80**
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Table A7.4. Variations from -10% to -100% of steel in relation to its weight-percentage in the composition used in the base case scenario.

C&DW composition	**Base case (%)**	**Variation in the weight-percentage of steel**									
		-10%	**-20%**	**-30%**	**-40%**	**-50%**	**-60%**	**-70%**	**-80%**	**-90%**	**-100%**
MixC&DW	**68.80**	**69.12**	**69.44**	**69.76**	**70.08**	**70.40**	**70.72**	**71.04**	**71.36**	**71.68**	**72.00**
Excavated soil	**18.10**	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10
Wood	**3.70**	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70
Gypsum	**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron and steel	**3.20**	**2.88**	**2.56**	**2.24**	**1.92**	**1.60**	**1.28**	**0.96**	**0.64**	**0.32**	**0.00**
Glass	**1.70**	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
Plastics	**1.50**	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Paper/Cardboard	**1.20**	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Mixed waste	**1.80**	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Table A7.5. Variations from -100% to +100% of glass in relation to its weight-percentage in the composition used in the base case scenario.

C&DW composition	**Base case (%)**	**Glass -100%**	**Glass -80%**	**Glass -60%**	**Glass -40%**	**Glass -20%**	**Glass +20%**	**Glass +40%**	**Glass +60%**	**Glass +80%**	**Glass +100%**
MixC&DW	**68.80**	**70.50**	**70.16**	**69.82**	**69.48**	**69.14**	**68.46**	**68.12**	**67.78**	**67.44**	**67.10**
Excavated soil	**18.10**	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10
Wood	**3.70**	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70
Gypsum	**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron and steel	**3.20**	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20
Glass	**1.70**	**0.00**	**0.34**	**0.68**	**1.02**	**1.36**	**2.04**	**2.38**	**2.72**	**3.06**	**3.40**
Plastics	**1.50**	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Paper/Cardboard	**1.20**	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Mixed waste	**1.80**	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Table A7.6. Variations from -100% to +100% of plastics in relation to its weight-percentage in the reference composition.

C&DW composition	**Base case (%)**	**Plastics -100%**	**Plastics -80%**	**Plastics -60%**	**Plastics -40%**	**Plastics -20%**	**Plastics +20%**	**Plastics +40%**	**Plastics +60%**	**Plastics +80%**	**Plastics +100%**
MixC&DW	**68.80**	**70.30**	**70.00**	**69.70**	**69.40**	**69.10**	**68.50**	**68.20**	**67.90**	**67.60**	**67.30**
Excavated soil	**18.10**	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10
Wood	**3.70**	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70
Gypsum	**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron and steel	**3.20**	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20
Glass	**1.70**	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
Plastics	**1.50**	**0.00**	**0.30**	**0.60**	**0.90**	**1.20**	**1.80**	**2.10**	**2.40**	**2.70**	**3.00**
Paper/Cardboard	**1.20**	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Mixed waste	**1.80**	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Table A7.7. Variations from -100% to +100% of paperboard in relation to its weight-percentage in the composition used in the base case scenario.

C&DW composition	**Base case (%)**	**Paper -100%**	**Paper -80%**	**Paper -60%**	**Paper -40%**	**Paper -20%**	**Paper +20%**	**Paper +40%**	**Paper +60%**	**Paper +80%**	**Paper +100%**
MixC&DW	**68.80**	**70.00**	**69.76**	**69.52**	**69.28**	**69.04**	**68.56**	**68.32**	**68.08**	**67.84**	**67.60**
Excavated soil	**18.10**	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10	18.10
Wood	**3.70**	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70
Gypsum	**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron and steel	**3.20**	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20
Glass	**1.70**	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
Plastics	**1.50**	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Paper/Cardboard	**1.20**	**0.00**	**0.24**	**0.48**	**0.72**	**0.96**	**1.44**	**1.68**	**1.92**	**2.16**	**2.40**
Mixed waste	**1.80**	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Table A7.8. Data changed due to variantions in the weight-percentage of wood in the C&DW composition.

C&DW management stages	**Base case**	**Wood (+10%)**	**Wood (+20%)**	**Wood (+30%)**	**Wood (+40%)**	**Wood (+50%)**	**Wood (+60%)**	**Wood (+70%)**	**Wood (+80%)**	**Wood (+90%)**	**Wood (+100%)**
Transport from sorting areas to landfill (tu_5) - mineral fraction	18836	18760	18679	18599	18519	18439	18359	18278	18198	18118	18038
Transport from sorting areas to landfill (tu_5) - wood	517	567	618	670	721	773	824	876	927	979	1030
Transport from sorting areas to landfill (tu_5) - mixed waste	11314	11459	11550	11640	11731	11822	11912	12003	12093	12184	12274
C&DW from sorting areas landfilling - mineral fraction	1651	1644	1637	1630	1623	1616	1609	1602	1595	1588	1581
C&DW from sorting areas landfilling - wood	32	35	39	42	45	48	52	55	58	61	64
C&DW from sorting areas landfilling - mixed waste	408,4	413	416	419	422	425	429	432	435	438	441
Transport from sorting area to recycling (tu_6) - mineral fraction	72524	72209	71901	71592	71283	70974	70665	70357	70048	69739	69430
Transport from sorting area to recycling (tu_6) - wood	21511	23662	25813	27964	30116	32267	34418	36569	38720	40871	43022
Mineral fraction recycling	1295	1289	1284	1278	1273	1267	1262	1256	1251	1245	1240
Wood recycling	283	311	339	367	395	424	452	480	508	537	565

Table A7.9. Data changed due to variantions in the weight-percentage of gypsum in the C&DW composition.

C&DW management stages	**Base case**	**Gypsum (+1%)**	**Gypsum (+2%)**	**Gypsum (+3%)**	**Gypsum (+4%)**	**Gypsum (+5%)**	**Gypsum (+6%)**	**Gypsum (+7%)**	**Gypsum (+8%)**	**Gypsum (+9%)**	**Gypsum (+10%)**
Transport from sorting areas to landfill (tu$_5$) - mineral fraction	18836	18623	18406	18190	17973	17756	17539	17322	17106	16889	16672
Transport from sorting areas to landfill (tu$_5$) - gypsum	0	2587	5174	7762	10349	12936	15523	18110	20698	23285	25872
C&DW from sorting areas landfilling - mineral fraction	1651	1632	1613	1594	1575	1556	1537	1518	1499	1480	1461
C&DW from sorting areas landfilling - gypsum	0	94	187	281	374	468	561	655	748	842	935
Transport from sorting area to recycling (tu$_6$) - mineral fraction	72524	71684	70849	70015	69180	68346	67511	66677	65842	65008	64173
Mineral fraction recycling	1295	1280	1265	1250	1246	1220	1205	1191	1176	1161	1146

Table A7.10. Data changed due to variantions in the weight-percentage of mixed waste in the C&DW composition (Part I).

C&DW management stages	**Base case**	**Mixed (+10%)**	**Mixed (+20%)**	**Mixed (+30%)**	**Mixed (+40%)**	**Mixed (+50%)**	**Mixed (+60%)**	**Mixed (+70%)**	**Mixed (+80%)**	**Mixed (+90%)**	**Mixed (+100%)**
Transport from sorting areas to landfill (tu$_5$) - mineral fraction	18836	18801	18762	18723	18684	18645	18606	18567	18528	18489	18450
Transport from sorting areas to landfill (tu$_5$) - mixed waste	11314	11834	12300	12766	13231	13697	14163	14629	15094	15560	16026
C&DW from sorting areas landfilling - mineral fraction	1651	1648	1644	1641	1637	1634	1631	1627	1624	1620	1617
C&DW from sorting areas landfilling - mixed waste	408	427	443	460	477	494	511	527	544	561	578
Transport from sorting area to recycling (tu$_6$) - mineral fraction	72524	72368	72218	72067	71917	71767	71617	71467	71316	71166	71016
Mineral fraction recycling	1295	1292	1289	1287	1284	1281	1279	1276	1273	1271	1268

Table A7.11. Data changed due to variantions in the weight-percentage of mixed waste in the C&DW composition (Part II).

C&DW management stages	**Mixed (+200%)**	**Mixed (+300%)**	**Mixed (+400%)**	**Mixed (+500%)**	**Mixed (+600%)**	**Mixed (+700%)**	**Mixed (+800%)**	**Mixed (+900%)**	**Mixed (+1000%)**	**Mixed (+200%)**	**Mixed (+300%)**
Transport from sorting areas to landfill (tu$_5$) - mineral fraction	18059	17669	17279	16889	16498	16108	15718	15328	14938	18059	17669
Transport from sorting areas to landfill (tu$_5$) - mixed waste	20683	25340	29996	34653	39310	43967	48624	53281	57938	20683	25340
C&DW from sorting areas landfilling - mineral fraction	1583	1549	1514	1480	1446	1412	1378	1343	1309	1583	1549
C&DW from sorting areas landfilling - mixed waste	746	915	1083	1251	1419	1588	1756	1924	2093	746	915
Transport from sorting area to recycling (tu$_6$) - mineral fraction	69514	68012	66510	65008	63505	62003	60501	58999	57497	69514	68012
Mineral fraction recycling	1241	1214	1188	1161	1134	1107	1080	1053	1027	1241	1214

Table A7.12. Data changed due to variantions in the weight-percentage of steel in the C&DW composition.

C&DW management stages	**Base case**	**Steel (-10%)**	**Steel (-20%)**	**Steel (-30%)**	**Steel (-40%)**	**Steel (-50%)**	**Steel (-60%)**	**Steel (-70%)**	**Steel (-80%)**	**Steel (-90%)**	**Steel (-100%)**
Transport from sorting areas to landfill (tu$_5$) - mineral fraction	18836	18909	18979	19048	19117	19187	19256	19326	19395	19464	19534
Transport from sorting areas to landfill (tu$_5$) - mixed waste	11314	11327	11286	11244	11203	11162	11120	11079	11037	10996	10955
C&DW from sorting areas landfilling - mineral fraction	1651	1657	1663	1669	1675	1682	1688	1694	1700	1706	1712
C&DW from sorting areas landfilling - mixed waste	408	408	407	405	404	402	401	399	398	396	395
Transport from sorting area to recycling (tu$_6$) - mineral fraction	72524	72785	73052	73319	73586	73853	74120	74387	74654	74921	75188
Transport from sorting area to recycling (tu$_6$) - steel	25484	22936	20387	17839	15291	12742	10194	7645	5097	2548	0
Mineral fraction recycling	1295	1300	1304	1309	1314	1319	1323	1328	1333	1338	1342
Steel recycling	284	256	227	199	171	142	114	85	57	28	0

Table A7.13. Data changed due to variantions in the weight-percentage of glass in the C&DW composition.

C&DW management stages	**Base case**	**Glass (-100%)**	**Glass (-80%)**	**Glass (-60%)**	**Glass (-40%)**	**Glass (-20%)**	**Glass (+20%)**	**Glass (+40%)**	**Glass (+60%)**	**Glass (+80%)**	**Glass (+100%)**
Transport from sorting areas to landfill (tu_5) - mineral fraction	18836	19208	19135	19061	18987	18914	18766	18692	18619	18545	18471
Transport from sorting areas to landfill (tu_5) - mixed waste	11314	9014	9480	9946	10412	10878	11811	12277	12743	13210	13676
C&DW from sorting areas landfilling - mineral fraction	1651	1683	1677	1670	1664	1658	1645	1638	1632	1625	1619
C&DW from sorting areas landfilling - mixed waste	408	324	341	358	375	392	425	442	459	476	493
Transport from sorting area to recycling (tu_6) - mineral fraction	72524	73937	73653	73369	73086	72802	72234	71951	71667	71383	71099
Transport from sorting area to recycling (tu_6) - glass	8214	0	1643	3286	4928	6571	9857	11499	13142	14785	16428
Mineral fraction recycling	1295	1320	1315	1310	1305	1300	1290	1285	1280	1275	1269
Glass recycling	284	0	15	30	45	60	90	105	120	134	149

Table A7.14. Data changed due to variantions in the weight-percentage of plastics in the C&DW composition.

C&DW management stages	**Base case**	**Plastics (-100%)**	**Plastics (-80%)**	**Plastics (-60%)**	**Plastics (-40%)**	**Plastics (-20%)**	**Plastics (+20%)**	**Plastics (+40%)**	**Plastics (+60%)**	**Plastics (+80%)**	**Plastics (+100%)**
Transport from sorting areas to landfill (tu_5) - mineral fraction	18836	19165	19100	19035	18970	18905	18775	18710	18645	18580	18515
Transport from sorting areas to landfill (tu_5) - mixed waste	11314	8308	8913	9519	10124	10729	11940	12546	13151	13756	14362
C&DW from sorting areas landfilling - mineral fraction	1651	1680	1674	1668	1663	1657	1645	1640	1634	1628	1623
C&DW from sorting areas landfilling - mixed waste	408	299	321	343	365	386	430	452	474	496	518
Transport from sorting area to recycling (tu_6) - mineral fraction	72524	73770	73519	73269	73019	72768	72268	72017	71767	71517	71266
Transport from sorting area to recycling (tu_6) - plastics	1278	0	256	511	767	1023	1534	1790	2045	2301	2557
Mineral fraction recycling	1295	1317	1313	1308	1304	1299	1290	1286	1281	1277	1272
Plastics recycling	31	0	6	12	19	25	37	43	49	56	62

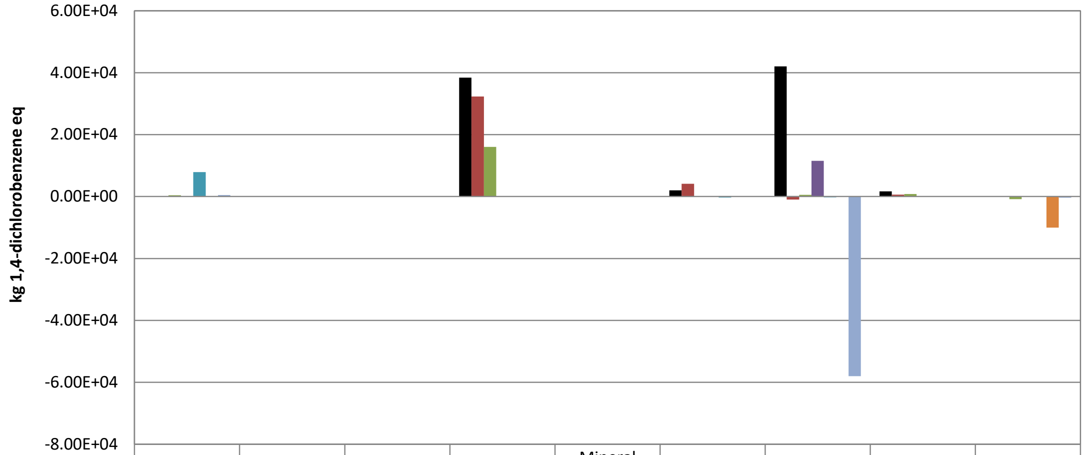
Table A7.15. Data changed due to variantions in the weight-percentage of paperboard in the C&DW composition.

C&DW management stages	**Base case**	**Paper (-100%)**	**Paper (-80%)**	**Paper (-60%)**	**Paper (-40%)**	**Paper (-20%)**	**Paper (+20%)**	**Paper (+40%)**	**Paper (+60%)**	**Paper (+80%)**	**Paper (+100%)**
Transport from sorting areas to landfill (tu_5) - mineral fraction	18836	19100	19048	18996	18944	18892	18788	18736	18684	18632	18580
Transport from sorting areas to landfill (tu_5) - paper	11314	0	621	1242	1863	2484	3726	4346	4967	5588	6209
C&DW from sorting areas landfilling - mineral fraction	1651	1674	1669	1665	1660	1656	1647	1642	1637	1633	1628
C&DW from sorting areas landfilling - paper	112	0	22	45	67	90	135	157	180	202	224
Transport from sorting area to recycling (tu_6) - mineral fraction	72524	73519	73319	73119	72919	72718	72318	72117	71917	71717	71517
Mineral fraction recycling	1295	1313	1309	1306	1302	1298	1291	1288	1284	1281	1277

APPENDIX A8 – SENSITIVITY ANALYSIS: LANDFILL MODELLING

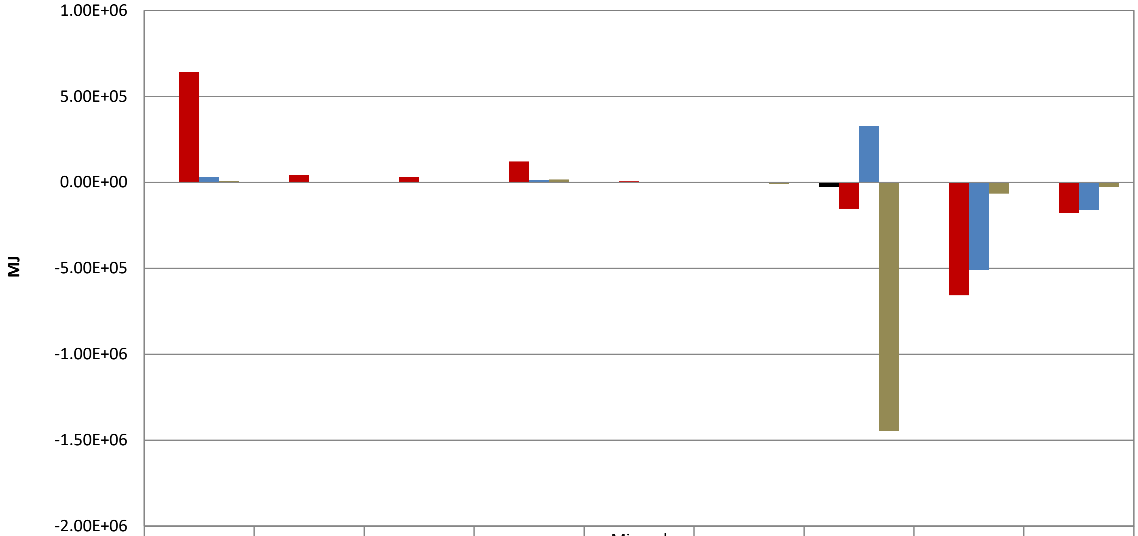
This appendix reports supplementary data of life cycle impact assesment obtained by using the CML baseline v3.03 methodology, including long-term emission.

Figure A8.1. Contribution analysis for the impact category "Human Toxicity" for the C&DW management system in the base case scenario (including long-term emission).



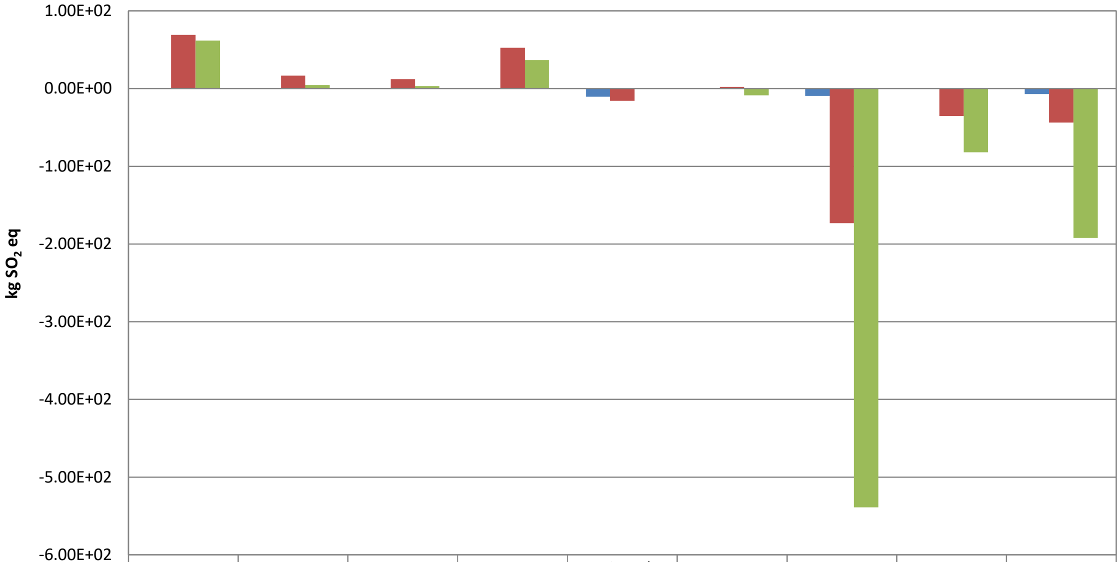
	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
■ Vanadium (water)	1.31E+01	7.17E-01	5.19E-01	3.84E+04	-1.91E+01	2.01E+03	4.21E+04	1.71E+03	-2.73E+01
■ Thallium (water)	1.37E+01	1.45E+00	1.05E+00	3.23E+04	9.99E-01	4.11E+03	-9.45E+02	6.01E+02	7.02E+00
■ Barium (water)	4.17E+02	2.63E+01	1.90E+01	1.60E+04	1.14E+01	-2.86E+01	5.65E+02	8.38E+02	-8.62E+02
■ Benzene, hexachloro- (air)	6.56E-03	3.37E-04	2.44E-04	9.47E-01	-1.75E-03	-1.97E-02	1.16E+04	2.28E-02	6.82E-01
■ Antimony (air)	7.89E+03	1.13E+00	8.15E-01	3.88E+00	-1.31E+01	-2.74E+02	-2.52E+02	-1.18E+01	-1.13E+02
■ Selenium (air)	5.37E+01	1.38E+00	1.00E+00	1.61E+01	-4.61E-01	-8.96E+00	-9.39E+01	-2.52E+01	-1.00E+04
■ Benzene (air)	4.99E+02	1.13E+01	8.19E+00	7.55E+01	1.02E+01	-8.20E+01	-5.80E+04	-5.89E+01	-3.48E+02

Figure A8.2. Contribution analysis for the impact category "Abiotic Depletion (fossil fuels)" for the C&DW management system in the base case scenario (including long-term emission).



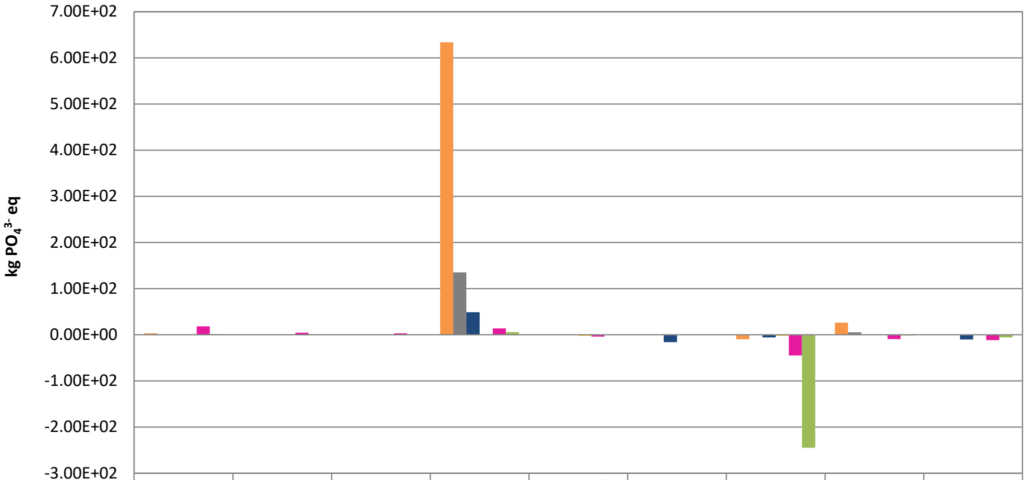
	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
■ Gas, coal mining/m³	1.46E+02	7.13E+00	5.16E+00	3.01E+02	-1.22E+01	-1.68E+02	-2.66E+04	-2.27E+02	-5.00E+02
■ Oil, crude	6.43E+05	4.14E+04	3.00E+04	1.22E+05	5.52E+03	-4.26E+03	-1.54E+05	-6.57E+05	-1.80E+05
■ Gas, natural/m³	2.97E+04	1.87E+03	1.35E+03	1.27E+04	1.01E+03	-4.01E+03	3.29E+05	-5.09E+05	-1.62E+05
■ Coal, hard	7.91E+03	3.87E+02	2.80E+02	1.61E+04	-5.81E+02	-8.95E+03	-1.45E+06	-6.60E+04	-2.66E+04

Figure A8.3. Contribution analysis for the impact category "Acidification" for the C&DW management system in the base case scenario (including long-term emission).



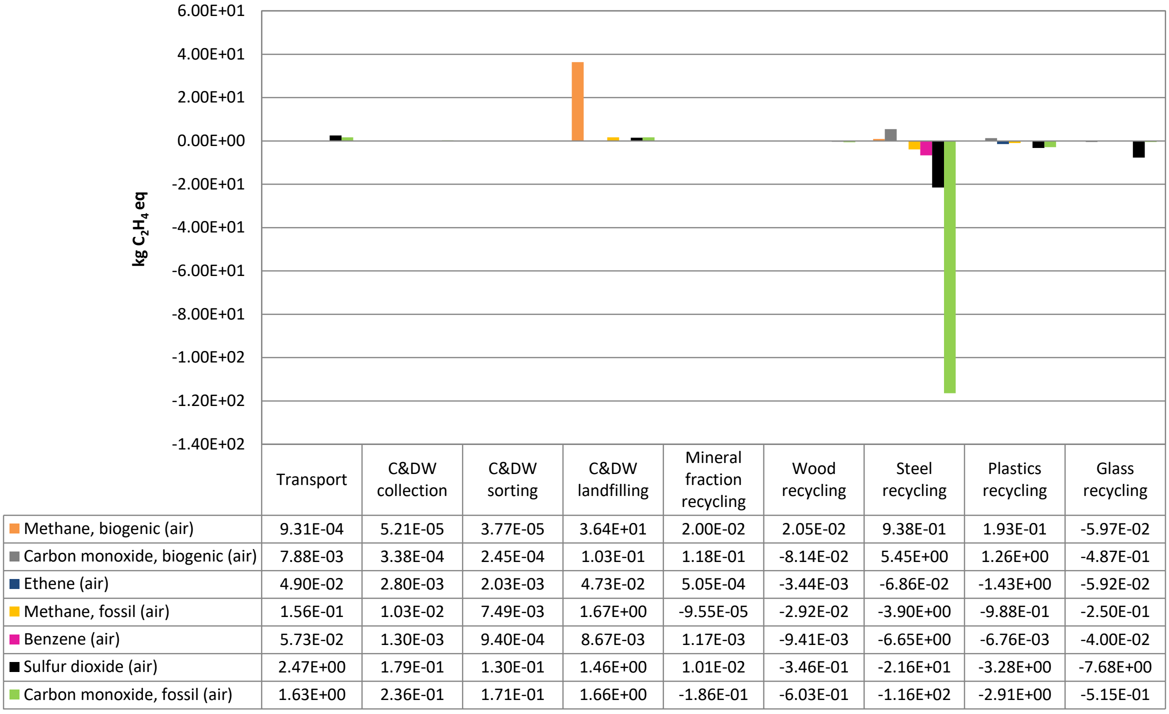
	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
🟦 Ammonia (air)	4.21E-01	2.90E-02	2.10E-02	5.09E-01	-1.05E+01	-1.05E-01	-9.32E+00	6.33E-01	-7.04E+00
🟥 Nitrogen oxides (air)	6.93E+01	1.67E+01	1.21E+01	5.27E+01	-1.56E+01	2.08E+00	-1.73E+02	-3.53E+01	-4.36E+01
🟩 Sulfur dioxide (air)	6.18E+01	4.48E+00	3.25E+00	3.66E+01	2.52E-01	-8.66E+00	-5.39E+02	-8.19E+01	-1.92E+02

Figure A8.4. Contribution analysis for the impact category "Eutrophication" for the C&DW management system in the base case scenario (including long-term emission).



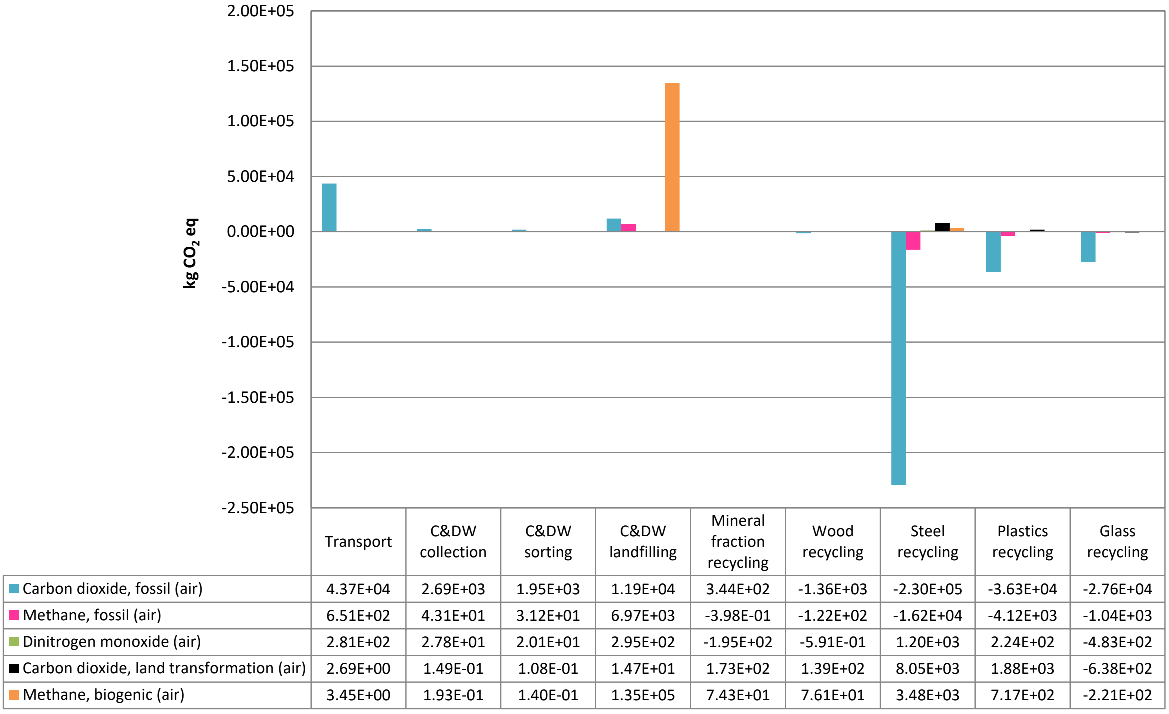
	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
🟧 Chemical Oxygen Demand (water)	3.04E+00	1.97E-01	1.43E-01	6.34E+02	3.45E-02	-7.06E-02	-9.74E+00	2.64E+01	-4.28E-01
⬛ Ammonium, ion (water)	3.07E-02	1.88E-03	1.36E-03	1.35E+02	-6.42E-03	-9.89E-03	-1.33E-02	5.43E+00	2.57E-02
🟦 Nitrate (water)	6.83E-01	4.45E-02	3.22E-02	4.91E+01	-8.34E-01	-1.62E+01	-5.63E+00	-2.98E-01	-1.02E+01
🟨 Ammonia (air)	9.20E-02	6.34E-03	4.59E-03	1.11E-01	-2.30E+00	-2.31E-02	-2.04E+00	1.38E-01	-1.54E+00
🟪 Nitrogen oxides (air)	1.80E+01	4.35E+00	3.15E+00	1.37E+01	-4.06E+00	5.41E-01	-4.50E+01	-9.18E+00	-1.13E+01
🟩 Phosphate (water)	1.38E+00	8.20E-02	5.94E-02	5.63E+00	1.58E-01	-1.06E+00	-2.45E+02	-1.65E+00	-5.77E+00

Figure A8.5. Contribution analysis for the impact category “Photochemical Oxidation” for the C&DW management system in the base case scenario (including long-term emission).



	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
■ Methane, biogenic (air)	9.31E-04	5.21E-05	3.77E-05	3.64E+01	2.00E-02	2.05E-02	9.38E-01	1.93E-01	-5.97E-02
■ Carbon monoxide, biogenic (air)	7.88E-03	3.38E-04	2.45E-04	1.03E-01	1.18E-01	-8.14E-02	5.45E+00	1.26E+00	-4.87E-01
■ Ethene (air)	4.90E-02	2.80E-03	2.03E-03	4.73E-02	5.05E-04	-3.44E-03	-6.86E-02	-1.43E+00	-5.92E-02
■ Methane, fossil (air)	1.56E-01	1.03E-02	7.49E-03	1.67E+00	-9.55E-05	-2.92E-02	-3.90E+00	-9.88E-01	-2.50E-01
■ Benzene (air)	5.73E-02	1.30E-03	9.40E-04	8.67E-03	1.17E-03	-9.41E-03	-6.65E+00	-6.76E-03	-4.00E-02
■ Sulfur dioxide (air)	2.47E+00	1.79E-01	1.30E-01	1.46E+00	1.01E-02	-3.46E-01	-2.16E+01	-3.28E+00	-7.68E+00
■ Carbon monoxide, fossil (air)	1.63E+00	2.36E-01	1.71E-01	1.66E+00	-1.86E-01	-6.03E-01	-1.16E+02	-2.91E+00	-5.15E-01

Figure A8.6. Contribution analysis for the impact category “Global Warming” for the C&DW management system in the base case scenario (including long-term emission).



	Transport	C&DW collection	C&DW sorting	C&DW landfilling	Mineral fraction recycling	Wood recycling	Steel recycling	Plastics recycling	Glass recycling
■ Carbon dioxide, fossil (air)	4.37E+04	2.69E+03	1.95E+03	1.19E+04	3.44E+02	-1.36E+03	-2.30E+05	-3.63E+04	-2.76E+04
■ Methane, fossil (air)	6.51E+02	4.31E+01	3.12E+01	6.97E+03	-3.98E-01	-1.22E+02	-1.62E+04	-4.12E+03	-1.04E+03
■ Dinitrogen monoxide (air)	2.81E+02	2.78E+01	2.01E+01	2.95E+02	-1.95E+02	-5.91E-01	1.20E+03	2.24E+02	-4.83E+02
■ Carbon dioxide, land transformation (air)	2.69E+00	1.49E-01	1.08E-01	1.47E+01	1.73E+02	1.39E+02	8.05E+03	1.88E+03	-6.38E+02
■ Methane, biogenic (air)	3.45E+00	1.93E-01	1.40E-01	1.35E+05	7.43E+01	7.61E+01	3.48E+03	7.17E+02	-2.21E+02

APPENDIX A9 – BRAZILIAN ENERGY MIX

This appendix reports an analysis of the Brazilian energy mix available in the Ecoinvent v.3.1 (2014) database.

Update of the Brazilian energy mix in the Ecoinvent v3.1 database

In order to update the Brazilian electric energy matrix available in the Ecoinvent v3.1 database, data from the National Electric Energy Agency (Aneel) were accessed in June 2018 (Table A9.1). Table A9.2 presents the comparison between data published by Aneel and those available in Ecoinvent v.3.1, according to the power supply.

Table A9.1. Brazilian energy mix according to Aneel (2018) (Part I).

Power Supply			Installed capacity		Total	
Source	**Source Level 1**	**Source Level 2**	**KW**	**%**	**KW**	**%**
Biomass	Agroindustrial	Sugarcane bagasse	11,220,435	6.6825	11,298,416	6.7289
		Biogas	948	0.0006		
		Grass	31,700	0.0189		
		Rice husk	45,333	0.0270		
	Liquid biofuels	Ethanol	320	0.0002	4,670	0.0028
		Vegetable oils	4,350	0.0026		
	Forest	Charcoal	43,197	0.0257	3,159,190	1.8815
		Blast Furnace Gas - Biomass	124,265	0.0740		
		Firewood	23,915	0.0142		
		Black liquor	2,542,616	1.5143		
		Forest residues	425,197	0.2532		
	Animal waste	Biogas	4,481	0.0027	4,481	0.0027
	Municipal solid waste	Biogas	133,129	0.0793	135,829	0.0809
		Coal	2,700	0.0016		
Wind	Wind kinetic	Wind kinetic	12,920,943	7.6952	12,920,943	7.6952
Fossil	Mineral coal	Process Heat	28,400	0.0169	3,717,830	2.2142
		Mineral coal	3,323,740	1.9795		
		Blast gas	365,690	0.2178		
	Natural gas	Process Heat	40,000	0.0238	12,999,978	7.7423
		Natural gas	12,959,978	7.7185		
	Other fossil	Process Heat	147,300	0.0877	147,300	0.0877
	Oil	Blast gas	1,200	0.0007	9,898,657	5.8953
		Refinery Gas	315,560	0.1879		
		Fuel oil	4,055,967	2.4156		
		Diesel oil	4,497,602	2.6786		
		Other from oil	1,028,328	0.6124		

Table A9.1. Brazilian energy mix according to Aneel (2018) (Part II).

Power Supply			Installed capacity		Total	
Source	**Source Level 1**	**Source Level 2**	**KW**	**%**	**KW**	**%**
Hydro	Hydraulic potential	Hydraulic potential	102,154,771	60.8395	102,154,771	60.8395
Nuclear	Uranium	Uranium	1,990,000	1.1852	1,990,000	1.1852
Solar	Solar radiation	Solar radiation	1,306,506	0.7781	1,306,506	0.7781
Undi-Elétric	Water kinetics	Water kinetics	50	0	50	0
Import	Paraguay		5,650,000	3.3649	8,170,000	4.8657
	Argentina		2,250,000	1.3400		
	Venezuela		200,000	0.1191		
	Uruguay		70,000	0.0416		
Total			**167,908,621**	**100**	**167,908,621**	**100**

Table A9.2. Grouped data of the Brazilian energy mix.

Power Supply	**Aneel (2018)**	**Ecoinvent v3.1** Electricity, high voltage {BR}| production mix | Alloc Def, U	**Ecoinvent v3.1** Electricity, high voltage {BR}| market for | Alloc Def, U
Hydro	60.84	78.63	70.79
Fossil	15.94	12.20	11.56
Biomass	8.70	6.20	5.96
Wind	7.70	0.14	0.13
Import	4.87	-	8.85
Nuclear	1.19	2.82	2.71
Solar	0.78	-	-

The update was performed on the process “**Electricity, high voltage {BR}| production mix | Alloc Def, U**” of Ecoinvent v3.1 (2014), according to the remarks presented in Table A9.3. Subsequently, the following datasets were also changed: “Electricity, high voltage {BR}| market for | Alloc Def, U”; “Electricity, medium voltage {BR}| market for | Alloc Def, U”; “Electricity, medium voltage {BR}| electricity voltage transformation from high to medium voltage | Alloc Def, U”; “Electricity, low voltage {BR}| market for | Alloc Def, U” and, “Electricity, low voltage {BR}| electricity voltage transformation from medium to low voltage | Alloc Def, U”.

Table A9.3. Details of the “Electricity, high voltage {BR}| production mix | Alloc Def, U” process of Ecoinvent v3.1 (2014) and values adopted in updating the data.

Power Supply	**Electricity, high voltage {BR}| production mix | Alloc Def, U - Ecoinvent v3.1 (2014)**	**%**	**Total (%)**	**Values adopted in updating the data**		
				%	**KW**	**Total (%)**
Biomass	cane sugar production with ethanol by-product	1.82	**6.20**	6.73	6.73E-02	**8.70**
	ethanol production from sugar cane	0.29		0.00	2.80E-05	
	heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014	4.09		1.97	1.97E-02	
Fossil	electricity production, hard coal	0.06	**12.20**	1.06	1.06E-02	**15.94**
	electricity production, lignite	1.35		0.94	9.38E-03	
	electricity production, natural gas, at conventional power plant	5.99		7.83	7.83E-02	
	electricity production, oil	3.62		5.89	5.89E-02	
	treatment of blast furnace gas, in power plant	0.82		0.00	7.00E-06	
	treatment of coal gas, in power plant	0.35		0.22	2.18E-03	
Hydro	electricity production, hydro, reservoir, tropical region	78.63	**78.63**	61.62	6.16E-01	**61.62**
Nuclear	electricity production, nuclear, pressure water reactor	2.82	**2.82**	1.19	1.19E-02	**1.19**
Wind	electricity production, wind, <1MW turbine, onshore	0.02	**0.14**	1.15	1.15E-02	**7.70**
	electricity production, wind, >3MW turbine, onshore	0.02		1.00	1.00E-02	
	electricity production, wind, 1-3MW turbine, onshore	0.10		5.54	5.54E-02	
Import	import from PY	0.00	**0.00**	3.36	3.36E-02	**4.87**
	import from AR	0.00		1.34	1.34E-02	
	import from VE	0.00		0.12	1.19E-03	
	import from UY	0.00		0.04	4.16E-04	
TOTAL		**100**	**100**	**100**	**1**	**100**

Tables A9.4 and A9.5 show the variation factor between the impacts of the generation of 1 MJ of energy according to the current LCI data (Ecoinvent v3.1) and the updated LCI (Ecoinvent v3.1 with modifications according to data from Aneel), based on CML baseline and Impact 2002+ methodologies, respectively.

According to the results obtained from the CML baseline methodology, the updated LCI presents the greatest impacts for all categories, with emphasis on “Abiotic Depletion”, with a increase of 116% and, “Photochemical Oxidation” with a increase of 112%. In relation to the other selected impact categories for this study, significant increases were observed for “Human Toxicity” (84%), “Acidification” (47%) and “Abiotic Depletion (fossil fuels)” (43%). “Global Warming” showed an increase of 6%.

Table A9.4. Life cycle impact assessment of 1 MJ of energy based on the current LCI (Ecoinvent v3.1) and updated LCI (Aneel, 2018). Data obtained by CML baseline.

Impact category	**Unit**	**Electricity, high voltage {BR}| production mix | Alloc Def, U**	**Electricity, high voltage {BR}| production mix | Alloc Def, U - modificado**	**VF**
Abiotic depletion	kg Sb eq	2.56E-09	5.52E-09	2.16
Photochemical oxidation*	kg C_2H_4 eq	2.59E-05	5.49E-05	2.12
Fresh water aquatic ecotox.	kg 1,4-DB eq	6.13E-04	1.12E-03	1.83
Terrestrial ecotoxicity	kg 1,4-DB eq	5.22E+00	8.37E+00	1.60
Human toxicity*	kg PO_4^{3-} eq	2.13E-05	3.39E-05	1.59
Marine aquatic ecotoxicity	kg 1,4-DB eq	2.73E-05	4.27E-05	1.56
Eutrophication	kg SO_2 eq	1.99E-04	2.92E-04	1.47
Acidification*	MJ	3.83E-01	5.47E-01	1.43
Abiotic depletion (fossil fuels)*	kg CFC-11 eq	2.91E-09	3.50E-09	1.20
Ozone layer depletion	kg 1,4-DB eq	4.87E-03	5.80E-03	1.19
Global warming*	kg CO_2 eq	5.96E-02	6.31E-02	1.06

Note: *Impact categories selected in this study.

According to the results obtained by Impact 2002+ methodology, the updated LCI has major impacts for all categories, except for “Respiratory Organics”, “Ionizing Radiation” and “Mineral Extraction”. The categories that presented the greatest increases were: “Non-Carcinogens” (191%), “Terrestrial Ecotoxicity” (172%), “Aquatic Ecotoxicity” (143%) and “Carcinogens” (142%). Considering the other categories selected for this study, there is an increase of 23% for “Non-Renewable Energy”, 9% for “Global Warming” and 1% for “Respiratory Inorganics”.

Table A9.5. Life cycle impact assessment of 1 MJ of energy based on the current LCI (Ecoinvent v3.1) and updated LCI (Aneel, 2018). Data obtained by Impact 2002+.

Impact category	**Unit**	**Electricity, high voltage {BR}| production mix | Alloc Def, U**	**Electricity, high voltage {BR}| production mix | Alloc Def, U - modificado**	**VF**
Non-carcinogens*	kg C_2H_3Cl eq	2.06E-02	5.99E-02	2.91
Terrestrial ecotoxicity	kg TEG soil	1.06E+00	2.88E+00	2.72
Aquatic ecotoxicity	kg TEG water	2.72E+00	6.60E+00	2.43
Carcinogens*	kg C_2H_3Cl eq	4.52E-03	1.09E-02	2.42
Land occupation	m^2org.arable	5.13E-03	8.64E-03	1.68
Aquatic acidification	kg SO_2 eq	1.91E-04	2.80E-04	1.46
Terrestrial acid/nutri	kg SO_2 eq	6.32E-04	9.16E-04	1.45
Non-renewable energy*	MJ primary	4.81E-01	5.91E-01	1.23
Ozone layer depletion	kg CFC-11 eq	2.91E-09	3.50E-09	1.20
Aquatic eutrophication	kg PO_4 P-lim	5.39E-06	6.25E-06	1.16
Global warming*	kg CO_2 eq	5.12E-02	5.58E-02	1.09
Respiratory inorganics*	kg $PM_{2.5}$ eq	5.99E-05	6.05E-05	1.01
Respiratory organics	kg C_2H_4 eq	9.85E-06	9.80E-06	0.99
Ionizing radiation	Bq C-14 eq	2.43E-01	1.72E-01	0.71
Mineral extraction	MJ surplus	7.69E-05	2.02E-05	0.26

Note: *Impact categories selected in this study.

The Figures A9.1 and A9.2 enable the comparison of the contribution of each energy source for the environmental impacts of 1 MJ energy, according to the current LCI (Ecoinvent v3.1) and updated LCI (Aneel, 2018), based on the CML baseline methodology.

Figura A9.1. Enviroamental impact contribution of the energy sources related to 1 MJ of energy based on the current LCI (Ecoinvent v3.1). Data obtained by CML baseline.

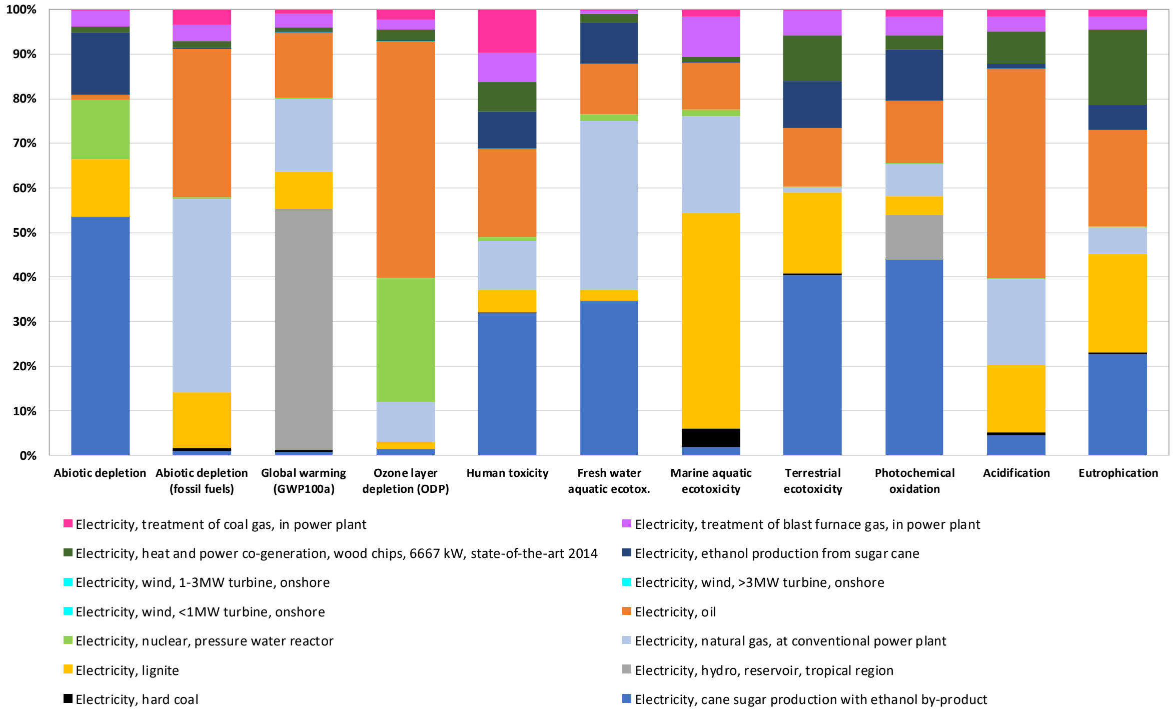
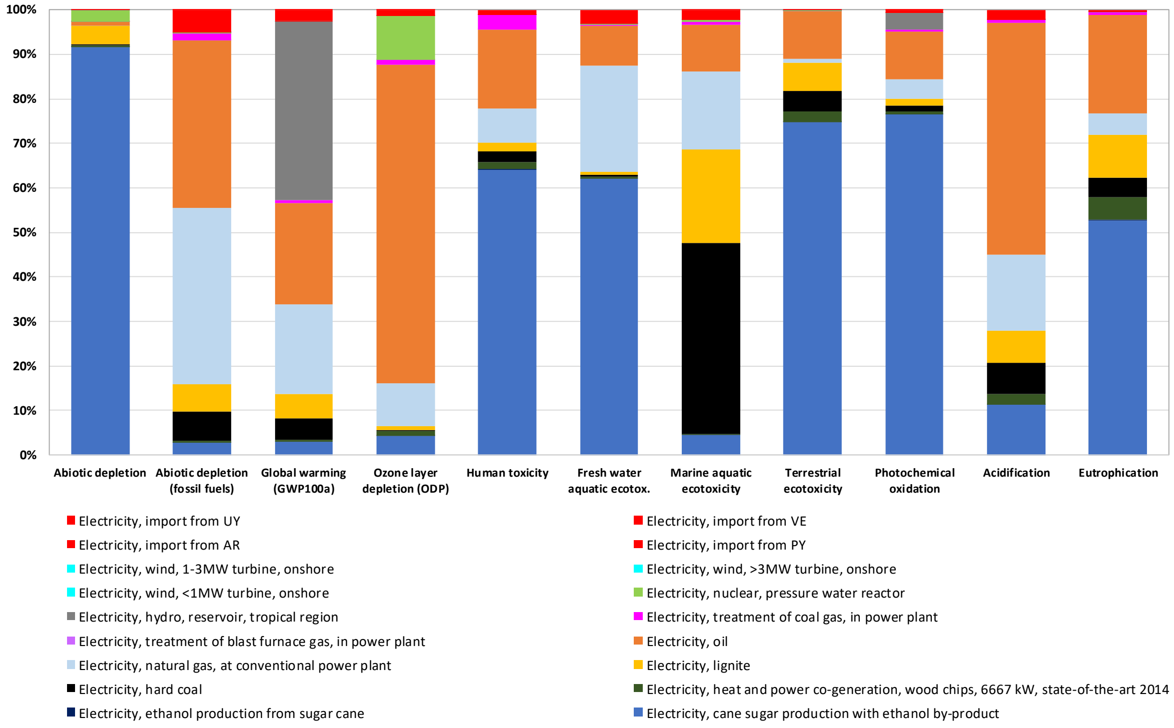


Figure A9.2. Enviroamental impact contribution of the energy sources related to 1 MJ of energy based on the updated LCI (Aneel, 2018). Data obtained by CML baseline.



It is possible to note that the largest amount of sugarcane bagasse reported in Aneel data is the factor responsible for the increase of the “Abiotic Depletion” impacts. The contribution analysis for this category indicated the emissions of iodine and bromine from the production of pesticides used in the cultivation of sugarcane as the main contributors. This energy source also justifies the increase of the “Photochemical Oxidation” impacts, due to the biogenic emissions from carbon monoxide. However, in this case there is still the participation of the emissions of sulfur dioxide and biogenic methane, the first one related to oil production and the second one with the generation of energy from hydroelectric plants.

For the “Eutrophication” and “Acidification” categories, the main energy sources that contributed to the impacts were oil, due to emissions of nitrogen oxides and sulfur (the latter only for "Acidification") and, emissions of nitrate (for "Eutrophication") and ammonia (for "Acidification") from the sugarcane cultivation.

For the categories “Abiotic Depletion (fossil fuels)” and “Human Toxicity”, the increase in impacts were justified by the greater share of natural gas and oil as energy sources. The latter also justifies the impact increase for “Global Warming”.

According to the results obtained by Impact 2002+ methodology, the sugarcane bagasse is the main contributor to the increase of impacts of “Non-Carcinogens”, “Carcinogens” and “Terrestrial Ecotoxicity”, due to the emissions of arsenic to the soil, and the last category also has a contribution of zinc emissions to the soil. This energy source also contributes to the “Aquatic Ecotoxicity” category due to the soil emissions of anthrax. The increases in impacts for the “Global Warming” and “Non-Renewable Energy” had the same justifications presented in the results obtained from the CML baseline methodology.

Figure A9.3. Enviroamental impact contribution of the energy sources related to 1 MJ of energy based on the current LCI (Ecoinvent v3.1). Data obtained by Impact 2002+.

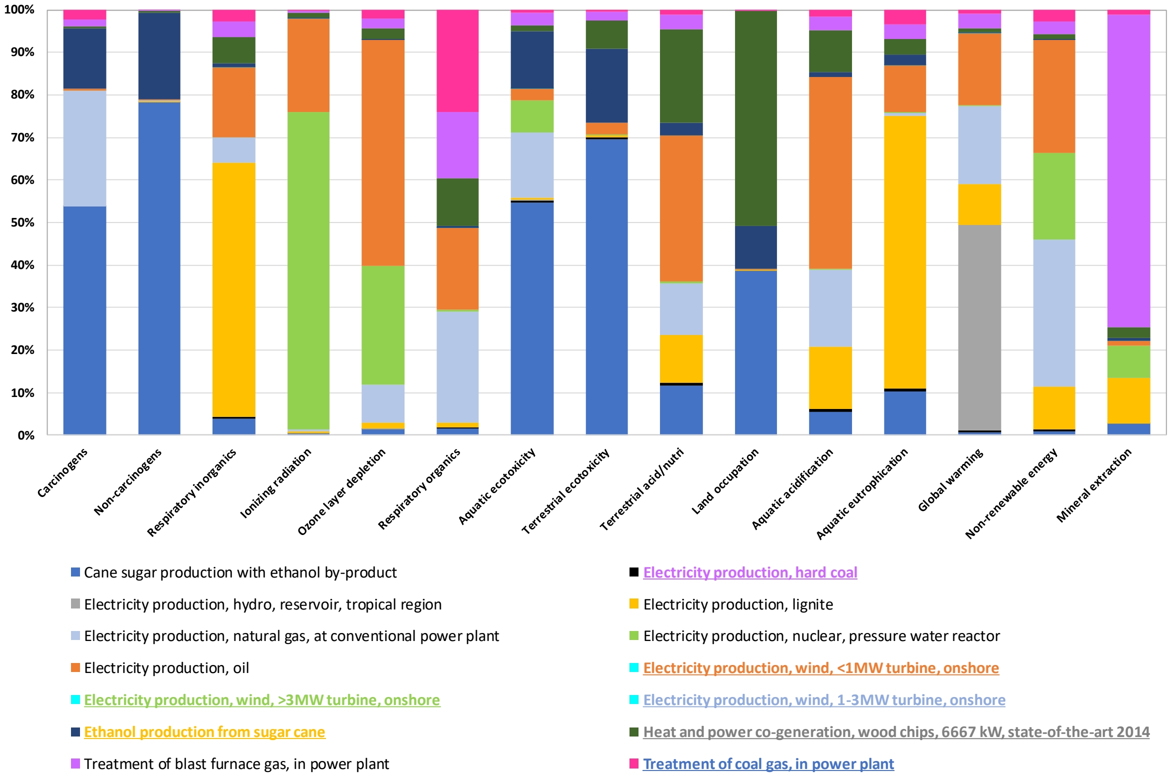
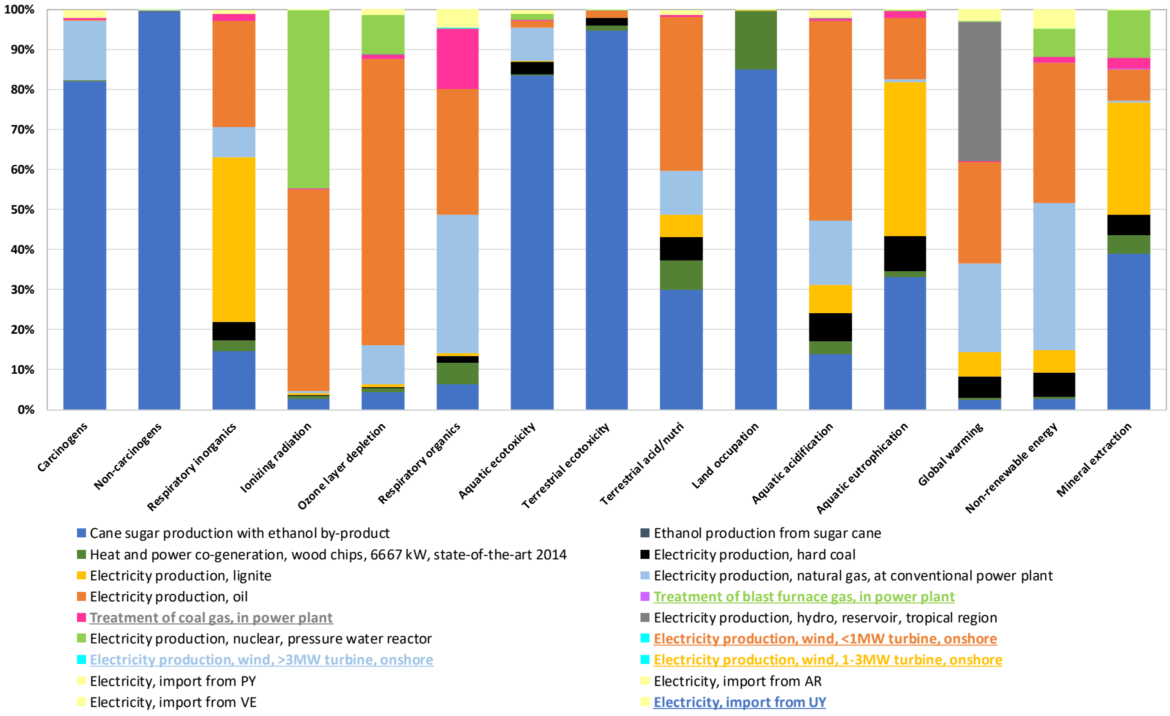


Figure A9.4. Enviroamental impact contribution of the energy sources related to 1 MJ of energy based on the updated LCI (Aneel, 2018). Data obtained by Impact 2002+ v2.12.



Despite the small contribution of sugarcane biomass to the Brazilian energy mix (approximately 7%), it was observed the important contribution of the impacts of sugarcane cultivation on the environmental profile of the Brazilian energy mix. In this sense, a careful evaluation of the inventory available in the Ecoinvent v3.1 database is required.

Coelho (2009) also highlighted the relevance of the impacts of this energy source to the "Carcinogens" category of the Eco indicator 99 H/A methodology, due to the emissions of arsenic to the soil. According to the author, the arsenic comes from the use of the diammonium phosphate fertilizer, which contains arsenic in its composition. However, the author pointed out that the data on pesticides used in the crop are from 1988. For this reason, the presence of aldrin in the inventory has also been observed (this substance was banned in Brazil since 1985). In this context, could be recommended to consider the characterisation factor of this substance as zero.

In addition, considering that it is an LCI based on not recent data, the harvest mechanization rate is low, therefore, there is a greater accounting of emissions from the burning of sugarcane due to the manual harvesting. On the other hand, if the mechanization rate were higher, there would be a higher diesel consumption.

Picoli *et al*. (2006) carried out the update of the process "sugarcane, at farm /BR U" of Ecoinvent database, based on data from the literature and expert consultation. According to this study, the main causes of the differences between the old and the updated data refer to the different types and quantities of fertilizers and pesticides, the occurrence of the mechanized harvesting (without burning) and accounting for greenhouse gas emissions from land-use change.

The comparison of the impacts of the cultivation of 1 tonne of sugarcane from the LCI available in the Ecoinvent v3.1 database and the updated LCI, using the ReCiPe Midpoint (H) v1.12/World ReCiPe H methodology, showed that "Terrestrial Ecotoxicity" is the main affected category, presenting 98% less impacts for the updated LCI. The main reason is the existence of the insecticide aldrin in the inventory available on Ecoinvent v3.1, and two other pesticides (the herbicides Atrazina and Linuron) were also included in much higher quantities.

Another important result was the reduction of 79% in the impacts of the category "Photochemical Oxidation" due to biogenic carbon monoxide emissions, derived from the burning of sugarcane in the manual harvesting, since the LCI of Ecoinvent v3.1 considers the practice of manual harvesting in 80% of the area, while the current average is 19%.

This study considered the use of the single superphosphate fertilizer in substitution to the diammonium phosphate fertilizer (DAP). Moreover, it was not considered the application of potassium in vinasse application area, nor the application of phosphorus in the area of application of cake filter.

Despite the variations highlighted above, the comparison between the environmental profile of the current base case scenario and the base case scenario with the modifications of the Brazilian energy mix and exclusion of the characterisation factor of "Aldrin" from the LCIA methodologies does not present significant differences in the characterised and normalised results.

Table A9.6 presents the results obtained by the CML baseline methodology and the variation factor for each category in ascending order. There is an increase in impacts due to changes in the energy mix for the "Fresh Water Aquatic Ecotoxicity" (14%), "Eutrophication" (14%), "Ozone Layer Depletion" (13%) and "Photochemical Oxidation" (12%).

Tables A9.7 and A9.8 present the normalised results and the contribution of each category to the total impacts, confirming that there are no significant changes in the results, since the hierarchy of importance of the impact categories is maintained.

Tabela A9.6. Comparison between the environmental profile of the current base scenario and the base scenario containing the updated Brazilian energy mix. Characterised results obtained by the CML baseline methodology, considering all impact categories.

Impact category	**Unit**	**Base case scenario**	**Base case scenario - updated**	**VF**
Fresh water aquatic ecotox.	kg 1,4-DB eq	2.65E+03	3.02E+03	**1.14**
Eutrophication	kg PO_4^{3-} eq	4.47E+01	5.08E+01	**1.14**
Ozone layer depletion	kg CFC-11 eq	2.16E-03	2.45E-03	**1.13**
Abiotic depletion	kg Sb eq	3.03E-01	3.04E-01	1.00
Terrestrial ecotoxicity	kg 1,4-DB eq	1.13E+04	1.13E+04	1.00
Marine aquatic ecotoxicity	kg 1,4-DB eq	-6.79E+07	-6.65E+07	0.98
Global warming	kg CO_2 eq	-9.71E+04	-9.49E+04	0.98
Abiotic depletion (fossil fuels)	MJ	-2.00E+06	-1.93E+06	0.97
Acidification	kg SO_2 eq	-8.55E+02	-8.13E+02	0.95
Human toxicity	kg 1,4-DB eq	-3.30E+04	-2.99E+04	0.91
Photochemical oxidation	kg C_2H_4 eq	-1.14E+02	-1.00E+02	**0.88**

Tabela A9.7. Comparison between the environmental profile of the current base scenario and the base scenario containing the updated Brazilian energy mix. Normalised results obtained by the CML baseline methodology, considering all impact categories.

Impact category	**Base case scenario - current**		**Base case scenario - updated**	
	Normalisation	**Contribution**	**Normalisation**	**Contribution**
Marine aquatic ecotoxicity	**-3.50E-07**	**89.70%**	**-3.43E-07**	**89.91%**
Human toxicity	-1.28E-08	3.27%	-1.16E-08	3.04%
Terrestrial ecotoxicity	1.03E-08	2.64%	1.04E-08	2.71%
Abiotic depletion (fossil fuels)	-5.25E-09	1.34%	-5.09E-09	1.33%
Acidification	-3.58E-09	0.92%	-3.41E-09	0.89%
Photochemical oxidation	-3.10E-09	0.79%	-2.72E-09	0.71%
Global warming	-2.32E-09	0.59%	-2.27E-09	0.59%
Abiotic depletion	1.45E-09	0.37%	1.45E-09	0.38%
Fresh water aquatic ecotox.	1.12E-09	0.29%	1.28E-09	0.33%
Eutrophication	2.83E-10	0.07%	3.21E-10	0.08%
Ozone layer depletion	9.54E-12	0.00%	1.08E-11	0.00%

Tabela A9.8. Comparison between the environmental profile of the current base scenario and the base scenario containing the updated Brazilian energy mix. Normalised results obtained by the CML baseline methodology, excluding “Marine Aquatic Ecotoxicity”, “Fresh Water Aquatic Ecotoxicity” and “Terrestrial Ecotoxicity” impact categories.

Impact category	**Base case scenario - current**		**Base case scenario - updated**	
	Normalisation	**Contribution**	**Normalisation**	**Contribution**
Human toxicity	**-1.28E-08**	**44.45%**	-1.16E-08	**43.17%**
Abiotic depletion (fossil fuels)	**-5.25E-09**	**18.23%**	-5.09E-09	**18.93%**
Acidification	**-3.58E-09**	**12.44%**	-3.41E-09	**12.67%**
Photochemical oxidation	**-3.10E-09**	**10.76%**	-2.72E-09	**10.13%**
Global warming	**-2.32E-09**	**8.06%**	-2.27E-09	**8.44%**
Abiotic depletion	1.45E-09	5.03%	1.45E-09	5.41%
Eutrophication	2.83E-10	0.98%	3.21E-10	1.20%
Ozone layer depletion	9.54E-12	0.03%	1.08E-11	0.04%

Table A9.9 presents the results obtained by the Impact 2002+ methodology and the variation factor for each category in ascending order. The main categories influenced by the modification of energy mix data were "Non-Carcinogens" and "Aquatic Ecotoxicity", with increases of 120% and 75%, respectively. Subsequently, the categories "Terrestrial Ecotoxicity", "Land Occupancy" and "Ozone Layer Depletion" showed a increase of 19%, 21% and 13%, respectively. Only, the category "Ionizing Radiation" showed a significant impact reduction (13%).

In relation to normalised results (Table A9.10), the hierarchy of importance of impact categories remains, however, it is important to note that the category "Non-Carcinogens" showed a significant increase in the contribution for the impacts.

Tabela A9.9. Comparison between the environmental profile of the current base scenario and the base scenario containing the updated Brazilian energy mix. Characterised results obtained by Impact 2002+ methodology, considering all impact categories.

Impact category	**Unit**	**Base case scenario - current**	**Base case scenario - updated**	**VF**
Non-carcinogens	kg C_2H_3Cl eq	1.57E+04	3.45E+04	**2.20**
Terrestrial ecotoxicity	kg TEG soil	4.49E+06	5.36E+06	**1.19**
Ozone layer depletion	kg CFC-11 eq	2.16E-03	2.45E-03	**1.13**
Carcinogens	kg C_2H_3Cl eq	4.02E+04	4.31E+04	1.07
Respiratory organics	kg C_2H_4 eq	-2.33E+02	-2.33E+02	1.00
Mineral extraction	MJ surplus	-5.81E+04	-5.82E+04	1.00
Respiratory inorganics	kg $PM_{2.5}$ eq	-2.36E+02	-2.35E+02	1.00
Global warming	kg CO_2 eq	-2.06E+05	-2.03E+05	0.99
Non-renewable energy	MJ primary	-2.16E+06	-2.12E+06	0.98
Aquatic acidification	kg SO_2 eq	-7.96E+02	-7.56E+02	0.95
Aquatic eutrophication	kg PO_4 P-lim	-8.18E+00	-7.70E+00	0.94
Terrestrial acid/nutri	kg SO_2 eq	-2.09E+03	-1.96E+03	0.94
Ionizing radiation	Bq C-14 eq	2.34E+05	2.05E+05	**0.87**
Land occupation	m^2org.arable	-8.12E+03	-6.39E+03	**0.79**
Aquatic ecotoxicity	kg TEG water	-2.79E+06	-9.83E+05	**0.35**

Tabela A9.10. Comparison between the environmental profile of the current base scenario and the base scenario containing the updated Brazilian energy mix. Normalised results obtained by the Impact 2002+ methodology, considering all impact categories.

Impact category	**Base case scenario - current**		**Base case scenario - updated**	
	Normalisation	**Contribution**	**Normalisation**	**Contribution**
Respiratory inorganics	**-2.33E+01**	**27.65%**	**-232E+01**	**25.08%**
Global warming	**-2.08E+01**	**24.70%**	**-2.05E+01**	**22.19%**
Carcinogens	**1.59E+01**	**18.84%**	**1.70E+01**	**18.39%**
Non-renewable energy	**-1.42E+01**	**16.87%**	**-1.40E+01**	**15.10%**
Non-carcinogens	**6.19E+00**	**7.35%**	**1.36E+01**	**14.70%**
Terrestrial ecotoxicity	2.60E+00	3.08%	3.10E+00	3.34%
Land occupation	-6.46E-01	0.77%	-5.08E-01	0.55%
Mineral extraction	-3.83E-01	0.45%	-3.83E-01	0.41%
Terrestrial acid/nutri	-1.59E-01	0.19%	-1.48E-01	0.16%
Respiratory organics	-7.00E-02	0.08%	-7.01E-02	0.08%
Ionizing radiation	1.02E-02	0.01%	6.07E-03	0.01%
Aquatic ecotoxicity	-1.02E-02	0.01%	-3.60E-03	0.00%
Ozone layer depletion	3.20E-04	0.0004%	3.63E-04	0.00%
Aquatic acidification	0.00E+00	-	0.00E+00	-
Aquatic eutrophication	0.00E+00	-	0.00E+00	-

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